Recommendations for Protecting Against Failure by Brittle Fracture in Ferritic Steel Shipping Containers Up to Four Inches Thick

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ABSTRACT

The brittle fracture of ferritic steels is discussed in terms of the degree of fracture toughness required to prevent failure of steel shipping containers used for transporting radioactive materials. The report includes: (1) recommended criteria and methods for controlling brittle fracture and (2) recommended procedures for designing shipping containers to have an appropriate level of safety against brittle fracture. A review of the elements of fracture mechanics, a synopsis of "Guidelines for Fracture-Safe Design of Steel Structures," and a discussion on margin of safety are included as appendix material.

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PREFACE AND ACKNOWLEDGMENTS

This report contains recommended criteria and methods of implementation for protecting ferritic steel shipping containers against failure by brittle fracture. The work was done by Lawrence Livermore National Laboratory (LLNL) and was funded by the Transportation Certification Branch, within the Office of Nuclear Material Safety and Safeguards of the Nuclear Regulatory Commission (NRC).

The recommendations represent the technical judgments of the authors resulting from consultations with four technical experts in the field of brittle fracture:

- Iain Finnie, Professor of Mechanical Engineering, University of California, Berkeley, CA.
- Eugene Lange, Naval Research Laboratory, Washington DC (retired).
- William Pellini, Naval Research Laboratory (retired).
- Stanley Rolfe, Professor of Civil Engineering, University of Kansas, Lawrence, KA.

While developing the recommendations the authors had numerous discussions with the NRC staff and ASME's Nuclear Packaging (NUPACK) Committee on Design. Recommendations and methods of analysis were selected to achieve an adequate margin of safety while allowing designers of shipping containers maximum flexibility in the choice of steels, techniques for fabrication, analysis, and final qualification.

Readers not familiar with the concepts of fracture mechanics may find it helpful to read Appendix A, which contains a brief review of the subject, before reading the body of the report.

The authors wish to thank C. R. Chappell for his contributions and support as the technical monitor of this project, and Hugh Keedy for his editorial help and technical support.

NOMENCLATURE

A	Temperature relative to NDT; $A = LST - T_{NDT}$
AAR	Association of American Railroads
AWS	American Welding Society
B	Section thickness
β	A dimensionless parameter $= \dfrac{1}{B}\left(\dfrac{K_{ID}}{\sigma_{yd}}\right)^2$
COD	Crack Opening Displacement
CVN, C_V	Charpy V-notch test or the test results
DWTT	Drop Weight Tear Test
DT	Dynamic Tear test or the test results
HAZ	Heat affected zone of welds
K_I	Stress intensity factor
K_{IC}	Critical value of K_I for static loading rates. When K_{IC} is exceeded, fracture occurs.
K_{ID}	Critical value of K_I for dynamic loading rates
$K_{I(t)}$	Critical value of K_I for intermediate loading rates.
LST	Lowest service temperature (lowest metal temperature)
(L)	Limit of plane strain
NDT	Nil Ductility Transition
Q&T	Quenched and Tempered
σ	Nominal stress (see glossary)
σ_{ys}	Yield strength for a static loading rate. This is considered the ASTM minimum yield for a specific steel.
σ_{yd}	Yield strength for dynamic loading rate $= \sigma_{ys} + 30$ ksi for steels with $\sigma_{ys} \leqslant 60$ ksi $= \sigma_{ys} + 15$ ksi for steels with $\sigma_{ys} \geqslant 70$ ksi $= \sigma_{ys} + 20$ ksi for steels with 60 ksi $< \sigma_{ys} < 70$ ksi
T_{NDT}	Nil Ductility Transition (NDT) temperature
(YC)	Yield Criterion; the level of toughness required to provide fracture arrest at a nominal stress equal to the yield strength.

1. EXECUTIVE SUMMARY

This report addresses the problem of brittle fracture in ferritic steels and recommends fracture toughness criteria that will provide three levels of safety in shipping containers licensed for transporting radioactive materials. Recommendations are given for defining three categories of fracture toughness criteria that will provide degrees of safety appropriate to the various materials transported in the containers. We also recommend that:

1. A fracture control plan be implemented for each container design.
2. Fracture-critical components be identified and treated as specified.
3. Specific fracture toughness testing requirements be established.
4. Appropriate specification and qualification procedures be adopted for all fracture critical welds.

A summary of the fracture toughness requirements for steels and the appropriate qualification tests for the three categories are shown in Table 1.

The largest margin of safety is provided in Category I by requiring sufficient toughness to assure that there is no crack propagation at the lowest service temperature. Steels with this level of toughness can tolerate large flaws under dynamic loading conditions.

A smaller margin of safety is allowed for Category II, in which the minimum level of toughness at the lowest service temperature is specified at somewhat above the level of toughness at the plane strain limit for dynamic loading conditions. If the shock mitigating system is effective in reducing the loading rate in the fracture critical components, then an intermediate loading rate can be assumed and an additional reduction in the minimum toughness is permitted for Category II.

The level of safety required for Category III is less than that for Category II, and the minimum toughness requirements are correspondingly reduced. Good engineering practices and selection of steels with a low NDT temperature make it unlikely that brittle fracture will occur.

A review of the elements of fracture mechanics, a synopsis of "Guidelines for Fracture-Safe Design of Steel Structures," and the engineering rationale for the three levels of safety are included as appendix material.

Category	Category I		Category II		Category III	
Required degree of safety (see Appendix C)	Very large margin of safety.		Large margin of safety.		Adequate margin of safety.	
Required amount of fracture toughness (see Sec. 5).	Sufficient to arrest large cracks under dynamic loading; general yielding will precede fracture.		Sufficient to prevent fracture initiation of pre-existing cracks under dynamic loading.		Sufficient to prevent fracture initiation at minor defects typical of good fabrication practices.	
	Thickness (B) (in.)	Criteria for meeting toughness requirements[a]	Thickness (B) (in.)	Criteria for meeting toughness requirements[a]	Thickness (B) (in.)	Criteria for meeting toughness requirements
	4.0 ↕ 0.625	*NDT temperature[b] must be less than a maximum value. See Fig. 4 and Secs. 5.1.1, 5.1.2. And, if $\sigma_{ys} \geq 70$ ksi, either: *5/8 in. thick DT[d] must be greater than 400 ft-lb at upper shelf temperatures. See Sec. 5.1.1. or *C_v[e] must be greater than 45 ft-lb at upper shelf temperatures. See Sec. 5.1.1.	4.0 ↕ 0.625	*With full dynamic loading; NDT temperature[c] must be less than a maximum value. See Fig. 6 and Sec. 5.2.1. Or *With reduced loading rates, NDT temperature can be determined from Fig. 7. See Sec. 5.2.2.	4.0 ↕ 0.4	*Without testing, use normalized steel made to "Fine Grade Practice" or better. Or show that: *NDT[c] ≤ 10°F (for B ≥ 0.625 in.) Or test to show that: *DT[d] ≥ 50 ft-lb at 10°F, with 0.625 in. test specimen. Or test to show that: *C_v[e] ≥ 15 ft-lb at 10°F. Or *Without testing, use as-rolled steel, provided welds have been stress relieved and inspected by nondestructive evaluation techniques. See Sec. 5.3.1.
	0.625 ↕ 0.19	*Use DT Test E-604-80. 80% or greater shear fracture required at LST. See Sec. 5.1.3. Or *Use DWTT Test E-436. 80% or greater shear fracture required at LST. See Sec. 5.1.3.	0.625 ↕ 0.19	*Use DT Test E-604-80. 50% or greater shear fracture required at LST. See Sec. 5.2.3. Or *Use DWTT Test E-436. 50% or greater shear fracture required at LST. See Sec. 5.2.3. Or *Use any normalized steel made to "Fine Grain Practice" or better. See Sec. 5.2.3.	0.4 ↕ 0.0	*No requirements when B is less than 0.4 in. thick. See Sec. 5.3.2.
	0.19 ↕ 0.025	*Use Notch Tensile Test E-338. $\dfrac{\text{Notch tensile strength}}{\text{yield strength}} \geq 1.0$ at LST.	0.19 ↕ 0.0	*No requirements when B is less than 0.19 in. See Sec. 5.2.3.		

[a]Full scale destructive testing on a case-by-case basis may be used as an alternate to requirements listed below.

[b]NDT is measured according to ASTM E-208, or an equivalent NDT can be established by subtracting 50°F from the midpoint of the 5/8 in. DT energy transition curve measured according to ASTM E-604.

[c]NDT is measured according to ASTM E-208, or an equivalent NDT can be established by subtracting 50°F from the midpoint of the 5/8 in. DT energy transition curve measured according to ASTM E-604, or the NDT temperature requirement can be met by selecting the maximum NDT temperature given in Fig. 1 or Table 3.

[d]DT measured according to ASTM E-604.

[e]C_v measured according to ASTM E-23.

2. INTRODUCTION

2.1 OBJECTIVES OF THIS REPORT

Objectives of the study upon which this report is based were:

1. To develop criteria that will control and prevent brittle fracture of shipping containers made of ferritic steels, under both normal and hypothetical accident conditions specified in the Code of Federal Regulations, Part 71.[1]

2. To recommend procedures for evaluating compliance of shipping containers with the suggested criteria.

3. To suggest classes of steels and procedures for qualifying those steels to meet the selected criteria.

2.2 SCOPE OF THIS REPORT

Brittle fracture, for the purposes of this report, is defined as a catastrophic failure that occurs at stress levels that develop before the occurrence of general yielding and subsequent ductile failure. Once started, the fracture may spread at speeds up to 7000 ft/s. Emerging techniques of elastic-plastic fracture mechanics, based upon such concepts as the J integral, are beyond the scope of this report. The procedures used in this study are based upon principles of linear elastic fracture mechanics and are applied to ferritic steels up to four inches thick with specified minimum static yield strengths up to and including 100 ksi.

We recommend that three categories of safety should be identified in the design of shipping containers. Design categories allow selection of an appropriate level of safety for the type of material being shipped.

Criteria for the three categories should identify:

1. The degree of safety required.

2. Methods of evaluating compliance, using assessment techniques compatible with current knowledge and technology in the fields of fracture toughness, stress analysis, and nondestructive evaluation.

Fracture toughness requirements, engineering rationale, and selection criteria for each of the three categories are summarized in Table 1 and discussed in terms of margin of safety in Appendix C. In Category I, containers are designed to the highest level of safety and brittle fracture is essentially not possible. In Category II, the level of safety is less than for Category I, and in this category it is important to control factors contributing to brittle fracture. In Category III, the required level of safety is less than that for Category II. In Category III good engineering practices and careful selection of material make brittle fracture unlikely under environmental conditions encountered during shipping.

The recommended procedures and criteria are adequate for accident or level D conditions (as specified in the ASME code) in which inelastic deformations may occur. A comprehensive fracture control plan that covers design, fabrication, welding, inspection, and operation of containers is beyond the scope of our recommendations.[2]

2.3 APPROACH

Our work began with a search for fracture control plans that might be applied to transportation containment vessels. Table 2 summarizes the fracture toughness requirements given in a recent review of many such plans.[2] This summary shows that toughness is generally specified in terms of Charpy V-notch tests, and that fracture mechanics is not applied directly to the design of most engineering structures. Exceptions to this general rule are:

● The aerospace industry, where high-strength, relatively low toughness materials are used for weight reduction, and where fatigue is a major failure mode.

● The nuclear pressure vessel industry, where the concepts of linear elastic fracture mechanics are applied by using the nil ductility transition (NDT) temperature as an indirect measurement of the fracture toughness of the steels.

● The North Sea drilling industry, where Crack Opening Displacement (COD) concepts have been applied to structural design of the drilling platforms.

After completing the survey, we decided to employ fracture mechanics techniques for the design of Categories I and II and a material toughness criterion for Category III. The material toughness requirements for Category III are stated in terms of

TABLE 2. Summary of fracture control plans.[a]

Industry	Steels (ferritic)	Toughness requirements (typical)	Notes
Ships and sea systems			
Merchant ships	ABS grades A to E and AH, DH and EH	CVN = 20 to 36 ft-lb at −40°C	For low temperature service, CVN = 30 ft-lb at 5°C below minimum design temperature.
LNG ships—Containment systems	ASTM—A353, A553	CVN = 30 ft-lb at −196°C	Secondary barrier required. "Leak before break" required.
Fixed offshore structures	API 2H, ASTM 537, 663 BS 4360	NDT ≤ (LST − 20°F)	Limited fracture mechanics (COD) analysis.
Floating nuclear power plant (support barge only)	ABS-CS steel	NDT = −30°F DT ≥ 250 ft-lb at +30°F	46 CFR 57 applies. Minimum air temp.: −5°F.
Steel structures			
LNG storage tanks	5% Ni, and 9% Ni steels	CVN = 25 ft-lb at −320°F	No fracture mechanics analysis. No initial damage assumptions.
Steel bridges	ASTM A36, A572, 588, 514	Varies with temp. zone	No initial damage assumptions. Allowable stress = $0.55\,\sigma_{ys}$.
Large rotating equipment (electric generator)	ASTM A469, A470, A471	No data. Proprietary specs.	Design based on successful history. Overspeed proof test.
Pressure vessels and piping			
Pressure vessels	See Codes SA-372, SA-36	CVN = 10 to 20 ft-lb at min. service temp. NDT < service temp. if min. temp. < −20°F.	No fracture mechanics used in Sec. VIII. No initial damage assumption. Proof test (1.25X).
Nuclear pressure vessels	See Codes	Uses K_{IR} curve. Requires NDT and CVN testing.	Assumes flaw = 1/4 wall thickness. Uses fracture mechanics in Sec. III.
Gas and oil pipelines	API 5L, 5LS, 5LU, 5LX	CVN = 50 ft-lb (−10°C)	Crack arrest capabilities for through-thickness cracks.
Pressure piping	Carbon 0.35%	CVN = 10–20 ft-lb min. at fluid temperature.	No fracture mechanics analyses; no initial damage assumptions.
Aerospace			
USAF aircraft	All MIL specs.	Crack arrest. Mostly fatigue design.	Fail-safe designs. Crack-arrest structure design. Initial flaw size assumptions.
NASA space vehicles (shuttle only)	All critical parts controlled in design, fabrication, testing and operation by a formal NASA-approved fracture-control plan.		Initial damage assumptions: 1. Cracks everywhere. 2. Initial size function of inspection method. 3. Fracture mechanics analyses must show 4X lifetime capability.

[a] From Ref. 2.

NDT temperature and Charpy V-notch or Dynamic Tear energy at specified temperatures. Our application of linear elastic fracture mechanics uses a dynamic critical stress intensity curve referenced to the NDT temperature and normalized to the dynamic yield stress (σ_{yd}) at NDT. This approach is used in the "Guidelines for Fracture-Safe Design of Steel Structures,"[3] which was developed for the Association of American Railroads (AAR), and in Sec. III of the ASME pressure vessel code, which was based on work reported in the Welding Council Research Bulletin 175. A synopsis of the AAR guidelines is given in Appendix B. The NDT temperature was also used as the fracture toughness parameter in a recently completed study for NRC on toughness requirements for steam generator supports in pressurized water reactors.[4]

As an alternative approach, we recommend that a specific container design may be qualified by full-scale survival drop tests. Qualification must be treated on a case-by-case basis and must include consideration of the following:

1. Lowest service temperatures.
2. Measured levels of material toughness.
3. Artificially induced cracks and flaws.

3. RECOMMENDED FUTURE WORK

The recommendations made in this report suggest a set of basic criteria along with procedures for evaluating compliance with these criteria. We also recommend that work be done in the following areas and that compliance procedures be refined as results of this work become available.

1. Develop techniques for producing artificial flaws of controlled sharpness, geometry, and location in fracture-critical components used in full scale survival tests.

2. Extend recommendations and criteria of this report to include emerging and future developments in fracture mechanics.

3. Develop experimental data on the fracture behavior of thin steel sections, and establish correlations with toughness data obtained from thicker sections of the same steel.

4. RECOMMENDATIONS

Recommendations in this report fall into two major groups. We first identify five tasks that need to be accomplished in establishing levels of safety and in qualifying shipping containers subject to brittle fracture. Next, we recommend testing methods for use in implementing the tasks.

In Sec. 5 we will recommend procedures for selecting and qualifying steels for each of three categories of safety.

4.1 RECOMMENDED PRACTICES

The following five tasks are deemed to be essential to establishing effective criteria to control brittle fracture in containers for shipping radioactive material. These tasks will include consideration of the variety of materials that might be shipped, the dynamic conditions of possible accidents, and the possibility that extreme environmental conditions could be encountered during shipment. We recommend that the NRC develop detailed guidelines for implementing these tasks.

Task 1: Define three categories of fracture toughness criteria. These categories should provide appropriate levels of safety against brittle fracture, considering the material transported in the containers. Our recommendations for defining the three categories are found in Sec. 5.

Task 2: Implement a fracture control plan for each container design. A suitable fracture control plan should be developed for each container design. Most elements of a comprehensive fracture control plan are already contained in paragraph 11.51 of 10 CFR 71 on quality assurance and in several Regulatory Guides (7.6, 7.7, 7.8).[5,6,7] Additional documentation should be required, with specific reference to material toughness criteria and to provisions for complying with the criteria in this report.

Task 3: Identify fracture-critical components of each container design. All fracture-critical components should be identified; i.e., those components whose failure by fracture could lead to penetration or rupture of the containment system. Specific application of the recommendations in this report should be made to all components identified as being fracture-critical.

Task 4: Establish fracture toughness testing requirements. Fracture toughness testing should be required on samples of steels used in each fracture-critical component in Category I systems. Qualification of steels for Category II and III systems can be either by fracture toughness testing or by use of the upper bound value of NDT to meet toughness criteria for a specific class of steel, as shown in Fig. 1 or Table 3.

When testing is required, the procedures in Sec. 4.2 specify the recommended fracture toughness tests.

Qualifying containment systems by full scale testing is a design option permitted by 10 CFR 71, where tests for normal conditions of transport and hypothetical accident conditions are specified. Section 4.2.2 of this report gives procedures for using the full scale testing option to establish the level of toughness required for fracture-critical components.

Task 5: Adopt specifications and qualification procedures for all fracture critical welds. We recommend adoption of the American Welding Society (AWS) system or equivalent ASME system for specification and qualification of welding procedures. We also recommend adoption of the AAR guidelines on welding, which will ensure that NDT temperature requirements for the base metal are met in all fracture-critical welds. These recommendations will require toughness measurement of welds according to specific procedures as well as certification that the same welding procedures are

TABLE 3.   NDT temperatures for steel plates.

Group	Group treatment	Thickness (in.)	NDT temperature range (°F)	ASTM specification
I. PEARLITIC: Low and intermediate strength steels (σ_{ys} = 30 to 70 ksi)				
	A As rolled	0.625 to 3	0 to 70	A36, A516, A709,
		3 to 4	20 to 90	A442, A662
	B Normalized (fine grain practice)	0.625 to 3	−50 to 10	A516, A442, A662,
		3 to 4	−30 to 30	A709
	C Normalized (high strength, low alloy)	0.625 to 3	−70 to −10	A441, A537, Cl 1,
		3 to 4	−50 to 10	A533, A588, A736
II. MARTENSITIC AND BAINITIC: High strength steels (σ_{ys} = 80 to 120 ksi)				
	D Quenched and tempered (low alloy)	0.625 to 4[a]	−90 to −30[b]	A514, A517
	E Quenched and tempered (high alloy)	0.625 to 4	−160 to −80[b]	HY-80, HY-100, A-508-CL 4 & 5, A543
III. CRYOGENIC STEELS: (σ_{ys} = 37 to 120 ksi at room temperature)				
	F See ASTM specifications	0.625 to 4	<−70°F[c]	A203
	G See ASTM	0.625 to 4	<−100°F[c]	A353, A553, A645

[a]Maximum thickness depends on hardenability.

[b]Manufacturer must certify that the NDT temperature is within this range.

[c]These steels are special cases. Each product should be tested by the DT test to determine the NDT temperature.
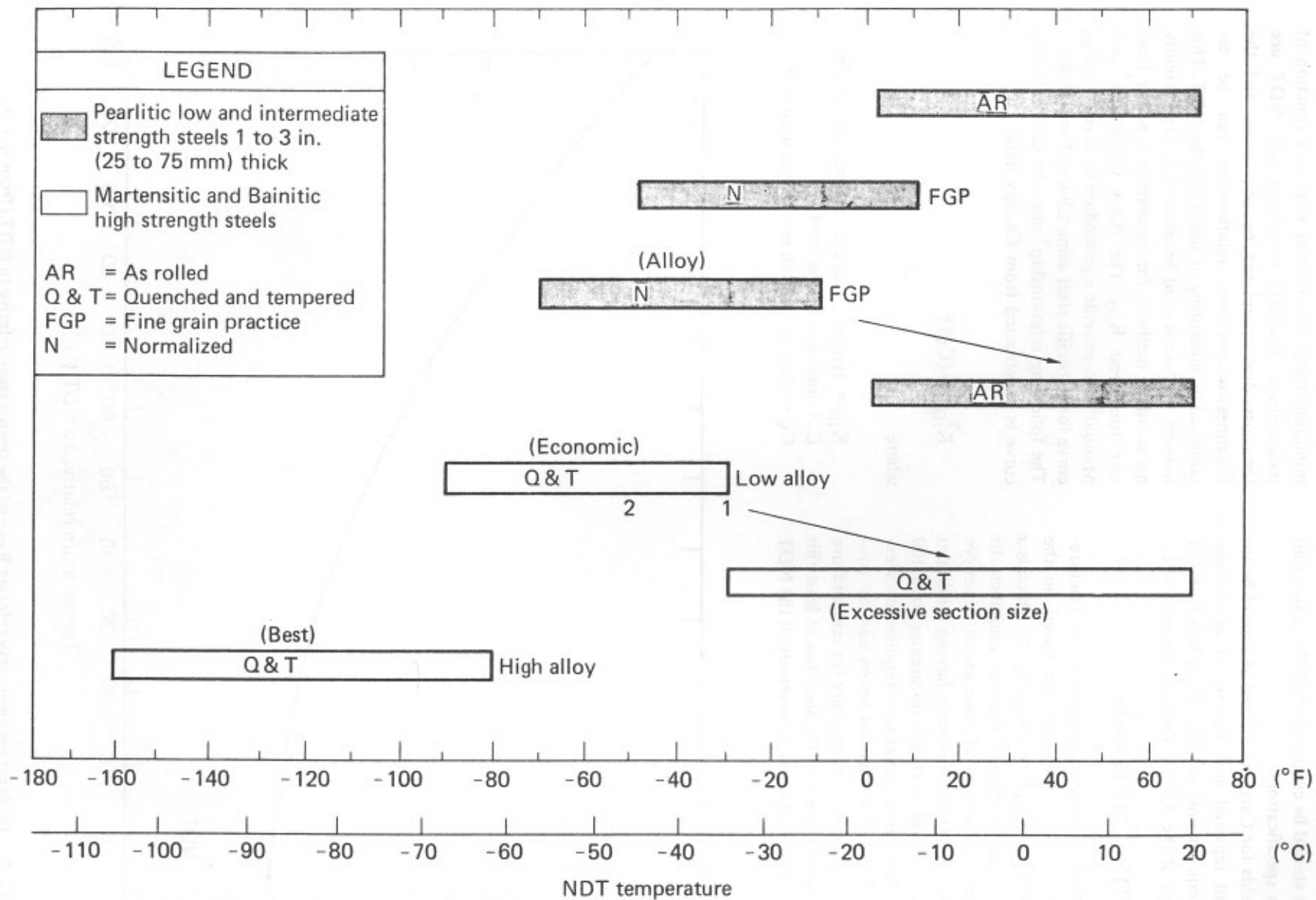
FIG. 1. Design-reference NDT temperatures for structural steels (from Ref. 3).

used for fabricating the structure. Welding procedures should be cited as part of the design and fabrication specifications.

All welds for Categories I and II should be inspected and repaired as necessary in accordance with the requirements of Sec. III, Class I and II respectively, of the ASME Pressure Vessel Code.

4.2 TESTING METHODS

The AAR guidelines procedures for fracture-safe design of steel structures are based on the Design Reference K_{ID} Curve (see Fig. 2), which is a lower bound curve relating fracture toughness to temperature relative to NDT. Our use of this curve will be limited to structural steels having minimum specified static yield strengths no greater than 100 ksi. Using this curve, toughness requirements expressed in fracture mechanics terms can be converted to the reference temperature (or temperature relative to NDT) at which the steel has at least this required level of toughness. Conversely, if the NDT temperature of a steel is known, the curve gives the minimum toughness of that steel as a function of temperature. Fracture toughness and NDT are therefore directly related by the curve, and the toughness-temperature relationship can be established by measuring or specifying the NDT. This indirect method is used because there are currently no standard methods for measuring dynamic fracture toughness K_{ID}. The AAR Guidelines[3] and Manual[8] also provide a procedure to develop a K_{ID} curve for a specific steel using Charpy V-notch data. The following relationship[9] must be used if a K_{ID} curve is constructed from Charpy data:

$$K_{ID}^2 = 5 (C_V) E$$

where

K_{ID} = dynamic fracture toughness in ksi $\sqrt{in}$.
E = modulus of the steel
C_V = Charpy V-notch measurement in ft-lb.

FIG. 2. Design-reference curve relating K_{ID} and the temperature relative to NDT (from Ref. 3).

This relationship is valid only for the lower half of the Charpy (C_V) curve.

4.2.1 The NDT Temperature

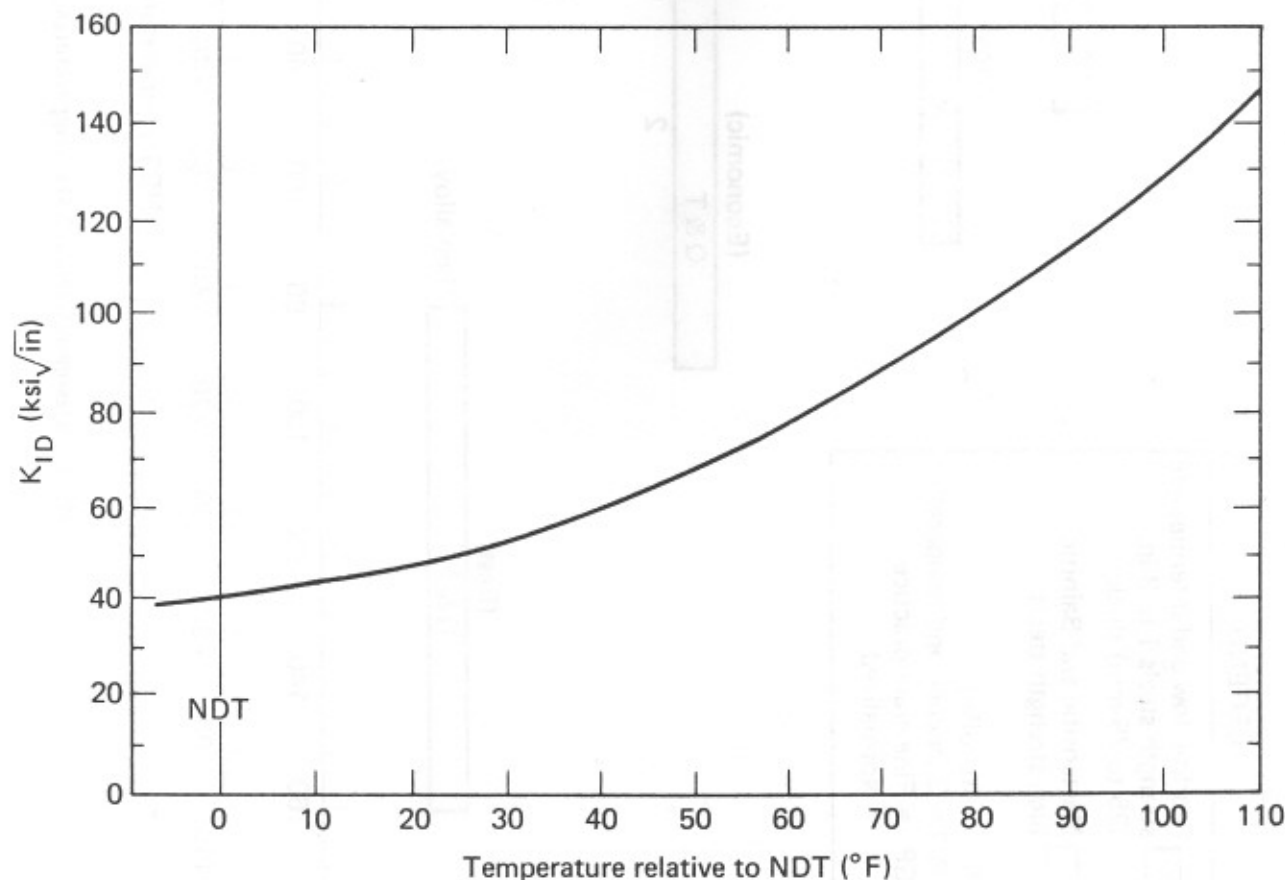The specification of the test method used to measure the NDT temperature (ANSI/ASTM E208-69, reapproved 1975) defines NDT temperature as "the maximum temperature where a standard drop-weight specimen breaks when tested according to the provisions of this test." When properly conducted, the test determines the temperature (within 10°F) above which the steel can withstand dynamic yield-point loading in the presence of a small flaw. On the design reference K_{ID} Curve (Fig. 2), the NDT temperature was conservatively set at the point where the K_{ID} curve starts to rise rapidly with temperature, i.e., at 40 ksi $\sqrt{in}$. Therefore, the NDT temperature defines the entire fracture toughness to temperature relationship for each structural steel. This fracture toughness parameter (NDT) is used throughout the AAR guidelines to characterize the fracture behavior required for different applications. NDT is a readily measurable material property that can be determined either directly by measurement or indirectly by correlation with other fracture toughness tests.

Direct measurement of the NDT temperature by the Drop Weight Test (ASTM E-208) is recommended. NDT values of higher strength steels (above σ_{ys} = 50 ksi) that are quenched and tempered may be less precise because the application of the brittle weld bead to the NDT test specimen can change the microstructure and local toughness of the steel.

The more recently developed Dynamic Tear test (ASTM E-604) is recommended as an alternate method for measuring the effective NDT of higher strength steels. With 5/8-in. thick Dynamic Tear test specimens, the NDT temperature can be reliably located at 50°F below the midpoint of the transition temperature range. This will locate the NDT temperature at a point where the dynamic tear energy curve starts bending upward with increasing temperature. When measured with Charpy V-notch tests, however, the transition temperature range is frequently quite broad and is generally located at lower temperatures than on the dynamic tear curve. For this reason, the NDT temperature cannot be determined reliably with Charpy V-notch tests unless enough NDT (or Dynamic Tear) tests have been conducted to demonstrate a reasonable correlation and temperature correction between the Charpy V-notch results and the NDT temperature for that particular grade of steel.

Differences between the Dynamic Tear test and the Charpy V-notch test are particularly important in determining the NDT temperature. Although similar to the Charpy V-notch test, the Dynamic Tear test differs in several ways. The specimen is larger, the notch is deeper and very sharp, and the fracture area is much greater. The measured fracture energy is considerably greater than for the Charpy V-notch specimen, and practically all of the energy is consumed in propagating the crack rather than in deforming the specimen before fracture begins. The Dynamic Tear test specimen consumes relatively little energy during fracture initiation since it is essentially a precracked specimen. Also, the specimen is large enough to provide for full development of the characteristic fracture mode and fracture propagation energy of the steel. In the Charpy test, which uses a large notch-radius and much smaller fracture area, much of the measured fracture energy is consumed in deforming the specimen before fracture begins.

A chart of NDT distribution data for different classes of steel is shown in Fig. 1. The values for NDT temperature given at the high end of each band can be used to meet the fracture toughness criteria for Category II and Category III. However, pressure vessel steels with improved values (lower values) of NDT temperature can generally be obtained for a given class of steels by adding supplementary requirements for toughness to the basic ASTM specification for pressure vessel steels. Use of these supplemental specifications generally makes it possible to procure steels with an NDT temperature certified to be near the center of the distribution band for that steel.

4.2.2 Full Scale Destructive Testing

An alternative to qualifying containment systems by analysis is to use full scale destructive testing of containers with artificial defects. The fact that containment is not breached by a full scale drop and/or puncture test (conducted in accordance with the hypothetical accident conditions of 10 CFR 71, and Regulatory Guides 7.6[5] and 7.8[7]) is accepted as evidence of design adequacy for that particular container. From a brittle fracture

standpoint, however, the design of subsequent containers is not adequate until all the following conditions are met:

1. The above drop or puncture test is satisfied.

2. The toughness of each fracture-critical component equals or exceeds the toughness of that component in the sample container tested.

3. No defects present in the containers are larger or more critically oriented than those in the tested system.

To meet the last two of these requirements, artificial defects should be introduced into the most critical areas of the system before the drop test. After the drop test, which should be conducted at the lowest service temperature, specimens from the fracture-critical components should be tested for fracture toughness using an approved standardized test such as the Charpy V-notch, Dynamic Tear, K_{Ic}, or COD to determine the level of toughness required in container systems using that design.

4.2.3 Testing For Thin Sections

Several testing methods have been standardized and approved by ASTM for characterizing the fracture behavior of thin sections (those less than 0.625 in. thick).

1. For sections thicker than 0.19 in., full section thickness Dynamic Tear tests (ASTM E-604-80) can be used to determine the transition temperature. If the fracture surface is at least 80% shear fracture at the lowest service temperature, then ductile fracture is assured.

2. For sections thicker than 0.19 in., ASTM E-436 can also be used to qualify the steel. If the fracture surface appearance at the lowest service temperature is greater than 80% shear, then ductile fracture is assured.

3. Another testing method (ASTM E-338) has been standardized and approved for characterizing the sharp notch tensile strength of sheet materials. This method can be used to qualify sections less than 0.19 in. thick at the lowest service temperature. This is a static test. There are no standardized dynamic testing methods for sections thinner than 0.19 in.

5. QUALIFICATIONS PROCEDURES ASSOCIATED WITH CATEGORIES OF SAFETY

In this section, procedures for selecting and qualifying steels for fracture critical components in each of three categories of safety are discussed.

Bolts are generally not considered as fracture-critical components because multiple load paths exist and because bolted systems are designed to be redundant. In other words, failure of one or more bolts can be tolerated since failure normally does not lead to penetration or rupture of the container. However, in cases where a particular bolt is determined to be a fracture-critical component, the toughness requirements for that bolt should be specified at the same category level as other components of the system.

5.1 CATEGORY I

A summary of fracture toughness requirements for Category I steels is shown in Table 4.

Of the three categories, the highest level of performance with respect to fracture safety is required in Category I. This highest level of safety is appropriate for containment systems for spent nuclear fuel and high-level waste transport packaging and other comparable packaging systems or components.

Fracture toughness testing is required on all steels used in Category I. fracture-critical components (Task 4 in Sec. 4.1).

Category I requirements represent the fracture-arrest conditions discussed in Appendix B and shown in Fig. 4. Fracture-arrest procedures given in the AAR guidelines, and summarized in Appendix B, are recommended for all fracture-critical components in this category. The minimum fracture-toughness requirements for fracture-critical components are specified at levels sufficiently high to prevent the extension of a through-thickness crack when the component is subjected to impact loading conditions that lead to stresses equal to the yield stress. For surface cracks, the critical crack size is shown in Fig. 5 as a function of

TABLE 4. Category I fracture toughness requirements and criteria for ferritic steels with yield strength no greater than 100 ksi.

Required degree of safety (see Appendix C)	Very large margin of safety.
Required amount of fracture toughness (see Sec. 5.1)	Sufficient to arrest large cracks under dynamic loading; general yielding will precede fracture.

Thickness (B) (in.)	Criteria for meeting toughness requirements[a]
0.625 to 4.0	• NDT temperature[b] must be less than a maximum value. See Fig. 3, and Secs. 5.1.1 and 5.1.2. Additionally, if the steel has $\sigma_{ys} < 70$ ksi, either: • 5/8 in. thick DT[c] must be greater than 400 ft-lb at upper shelf temperatures. See Sec. 5.1.1. Or • C_V[d] must be greater than 45 ft-lb at upper shelf temperatures. See Sec. 5.1.1.
0.19 to 0.625	• Use DT Test E-604-80. 80% or greater shear fracture appearance required at LST. See Sec. 5.1.3. Or • Use DWTT Test E-436. 80% or greater shear fracture appearance required at LST. See Sec. 5.1.3.
0.025 to 0.19	• Use Notch Tensile Test E-338. $\dfrac{\text{Notch tensile strength}}{\text{yield strength}} \geq 1.0$ at LST. See Sec. 5.1.3.

[a]Full scale destructive testing on a case-by-case basis may be used as an alternate to requirements listed below. See Sec. 5.1.4.

[b]NDT is measured according to ASTM E-208, or an equivalent NDT can be established by subtracting 50°F from the midpoint of the 5/8 in. DT energy transition curve measured according to ASTM E-604.

[c]DT measured according to ASTM E-604.

[d]C_V measured according to ASTM E-23.

K_{ID}/σ_{yd} for several stress levels. It should be emphasized that Fig. 5 should not be used when the flaw depth is more than half the section thickness or plane strain conditions do not exist.

Recommended procedures for selecting and qualifying Category I steels are discussed in Sec. 5.1.1. The basic requirements are modified for special situations in which the maximum applied stress is below the yield stress (Sec. 5.1.2), the sections used are thin (Sec. 5.1.3), or full-scale destructive testing is performed (Sec. 5.1.4).

5.1.1 Basic Qualifying Procedures (0.625 in. to 4.0 in. thick sections)

Dynamic loading to a stress equal to the dynamic yield strength is assumed (see Sec. 5.1.2 for exceptions), as is a lowest service temperature (Regulatory Guide 7.8[5]). Specific recommended criteria for Category I steels in the thickness range from 0.625 to 4.0 in. are:

1. The NDT temperature of the steel used must be less than the maximum NDT temperature

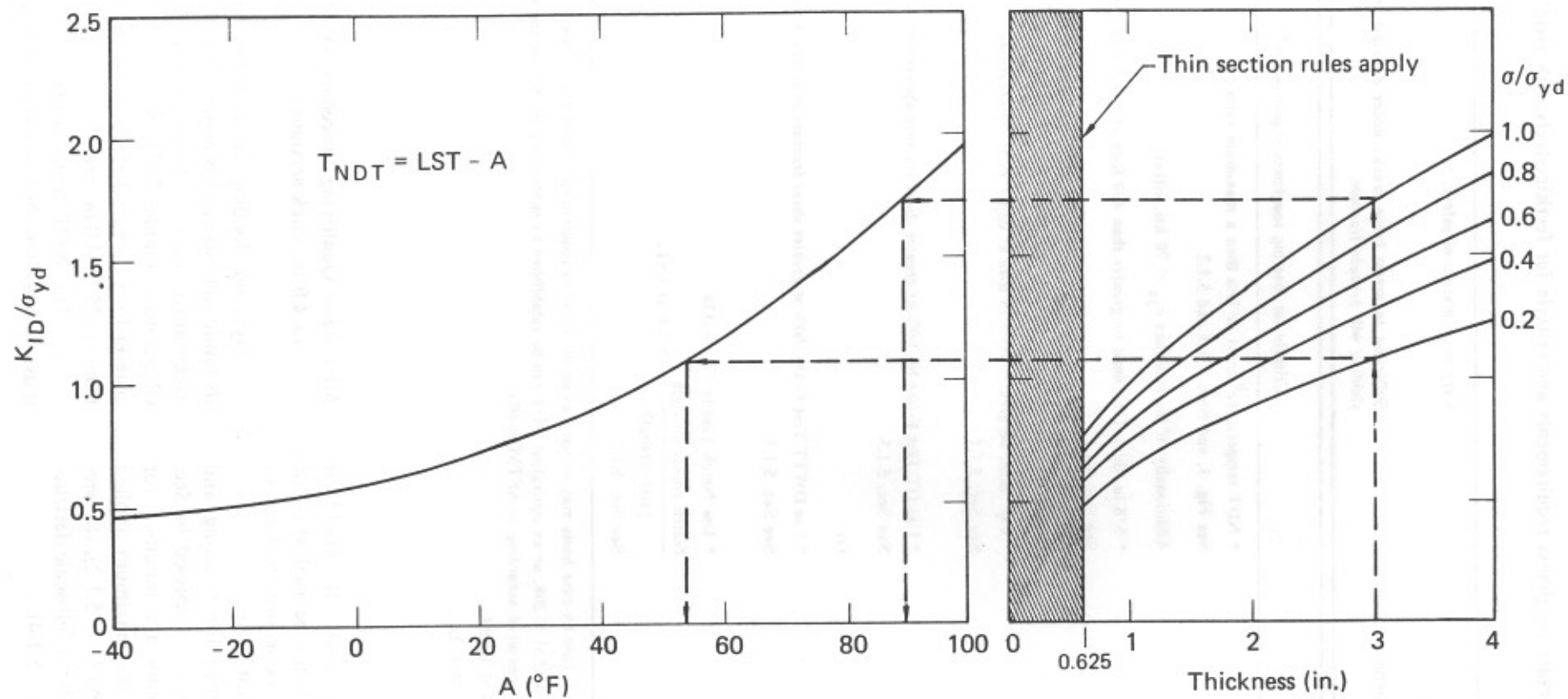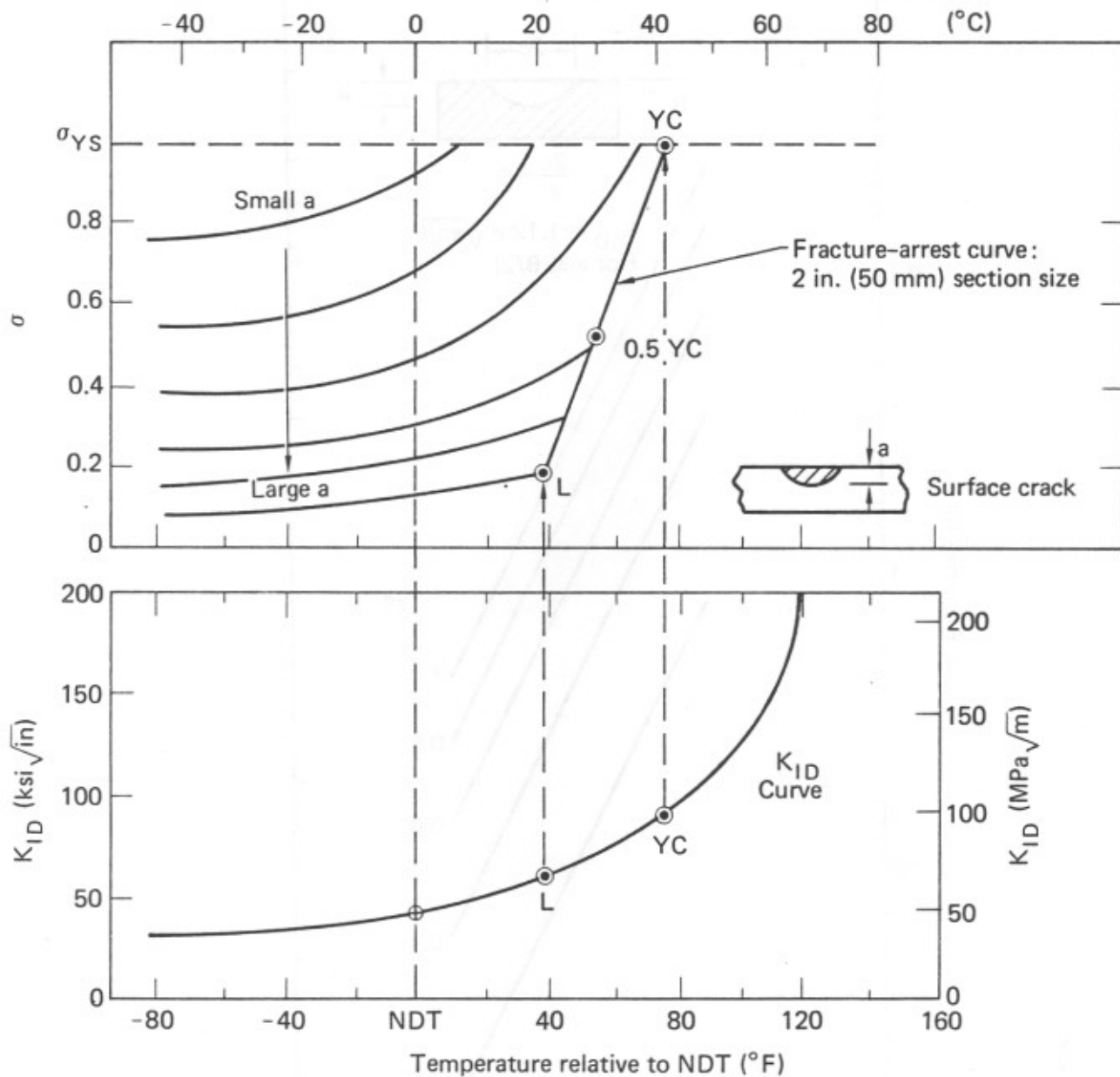FIG. 3. Design chart for Category I fracture critical components.

FIG. 4. Relationship of the fracture-initiation and fracture-arrest curves to the design-reference K_{ID} curve of Fig. 2 (from Ref. 3).
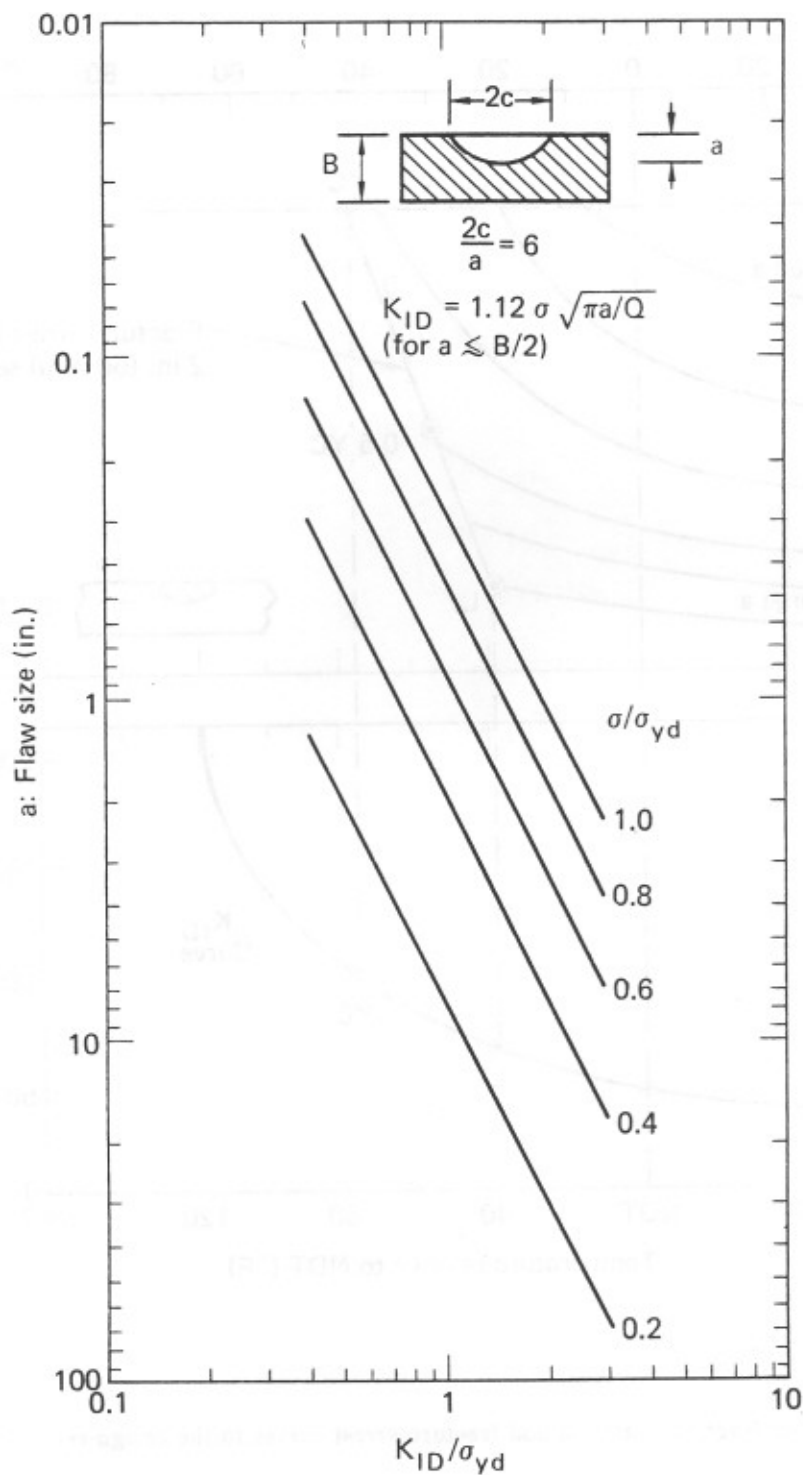
FIG. 5. Critical flaw size for several ratios of σ/σ_{yd}. Curves are valid only under plane strain conditions and for flaws less than half the plate thickness. Values of Q may be obtained from Fig. 11.

given in Fig. 3 for the thickness being used. The NDT temperature may be measured according to ASTM E-208, or may be calculated by subtracting 50°F from the midpoint of the 5/8 in. DT energy transition curve measured according to ASTM E-604.

2. In addition, if the yield strength of the steel is 70 ksi or greater, the 5/8 in. DT (as determined by ASTM E-604) must be greater than 400 ft-lb, or the C_V Charpy energy (as determined by ASTM E-23) must be greater than 45 ft-lb at upper shelf temperatures.

Allowable modifications to these basic qualifying procedures are discussed in Sec. 5.1.2.

When the stress is at the yield level (at (YC) in Fig. 4), the toughness of a Category I steel is high enough so that fracture can take place only after general yielding (gross overload) has occurred. To meet the fracture-arrest criteria under basic Category I loading conditions, the container must have at least the dynamic fracture toughness K_{ID} defined by the yield criterion (YC). To assure this toughness, β must be equal to or greater than 1.0 (see Eq. A-2 in Appendix A). When the dynamic stress is equal to the dynamic yield stress, the required NDT value for the steel can be determined from Fig. 3 as follows. Starting at the given section thickness, proceed vertically to a point on the σ/σ_{yd} curve having a value of 1.0, then horizontally from that point to a point on the K_{ID}/σ_{yd} curve, and from that point vertically to the A scale on the horizontal axis. The maximum allowable value of the NDT temperature is then the difference between the lowest service temperature (LST) and the value of A obtained (i.e., T_{NDT} = LST - A). If A is negative, then T_{NDT} is greater than LST since A is algebraically subtracted from LST. The example in Fig. 3 shows that a value of A = 88°F correlates with a plate thickness of 3.0 in. for yield level stresses.

The above procedure is based on the design-reference curve (Fig. 2), which relates the toughness of the steel (K_{ID}) to a temperature relative to the NDT temperature. Using this relationship, K_{ID} toughness requirements normalized to the dynamic yield stress can be specified in terms of the maximum allowable NDT temperature.

5.1.2 Qualifying Procedures for Reduced Stress Levels (0.625 in. to 4.0 in. thick sections)

For designs in which it can be shown that the maximum stresses in fracture-critical components are significantly below the dynamic yield strength, the required NDT temperature of the steel can be determined from Fig. 3 by entering with the appropriate section thickness and value of σ/σ_{yd}. The minimum toughness requirement is thereby reduced from the point (YC) along the fracture-arrest curve (in Fig. 4) toward the point (L) in proportion to the drop in maximum stress, as discussed in Appendix B. Reducing the maximum component stress to below yield stress permits the presence of flaws smaller than the size limit determined by the interrelationship among section thickness, stress level, and toughness, defined as the fracture-arrest criteria in Appendix B. That is, Category I toughness requirements will be satisfied if the stress intensity for a particular combination of flaw size and stress does not exceed the level defined by the fracture-arrest curve.

Figure 3 contains an example wherein the value of A = 53°F is found to correspond to a thickness of 3.0 in. and a ratio of σ/σ_{yd} = 0.2.

5.1.3 Qualifying Procedures for Thin Sections (0.025 in. to 0.625 in. thick)

Components thinner than 0.625 in. are considered thin sections and cannot be analyzed using Fig. 3.

For sections between 0.19 in. and 0.625 in. thick, either of the two following tests may be conducted to qualify steels:

1. Full section thickness Dynamic Tear tests as specified in ASTM E-604-80 may be used. Steels will be qualified if upper-shelf dynamic tear toughness levels (80% shear fracture appearance) are achieved at the lowest service temperature.

2. The Battelle Drop Weight Tear Test (ASTM E-436) has been standardized and is also available for evaluating the fracture toughness of sections between 0.19 and 0.625 in. thick. This test, which is similar to the Dynamic Tear Test (ASTM E-604), uses fracture appearance to estimate the level of toughness at the test temperature. If at least

an 80% shear fracture surface is observed at the lowest service temperature, then the fracture toughness of the material is sufficient to prevent brittle fracture.

For sections less than 0.19 in. but more than 0.025 in. thick, notch tensile tests (ASTM E-338) should be used at the lowest service temperature. For Category I steels, the notch tensile strength shall equal or exceed the yield strength.

5.1.4 Qualifying by Full Scale Destructive Testing

The procedure recommended in Sec. 4.2 for qualifying containers by full-scale destructive testing is an alternative that should only be considered on a case-by-case basis for Category I containment systems. Selection of flaw sizes, geometry, location, and orientation, as well as the method used to introduce the flaws should be based on considerations of design, stress analysis, construction materials, fabrication processes, and nondestructive inspection capabilities. Each case study should specifically discuss the probability that larger or more damaging flaws than those artificially introduced might be present in the system being qualified. The geometry, orientation, and locations of artificial flaws should be well within detection limits—flaws should be at least twice as large as the lower limit of flaws detectable with the nondestructive evaluation techniques being used. Fracture-toughness tests should be made on specimens taken from successfully tested containers to determine the minimum toughness level required for the design.

5.2 CATEGORY II

A summary of fracture toughness requirements for Category II steels is shown in Table 5.

The level of performance with respect to fracture safety necessary for Category II is less than that required for Category I. For Category II systems, fracture toughness must be sufficient to prevent fracture initiation of pre-existing cracks under dynamic loading.

With Category II steels, fracture toughness (or the corresponding temperature relative to NDT) must be greater than that needed to exceed plane strain conditions ($\beta = 0.4$) under dynamic loading. We recommend that in defining the Category II

toughness requirement a value of $\beta = 0.6$ be used in the equation:

$$\beta = \frac{1}{B} \left(\frac{K_{ID}}{\sigma_{yd}} \right)^2$$

where σ_{yd} is the dynamic yield stress (as defined in the Nomenclature list), K_{ID} is the critical dynamic stress intensity, and B is the section thickness.

Using $\beta = 0.6$ in the above equation raises A (the temperature relative to NDT temperature) to a reasonable value for 1.0 in. thick sections. For example, with $\beta = 0.6$ and a 1.0 in. section thickness, the critical flaw size would be larger than 0.15 in. at yield stress loading.

Recommended procedures for selecting and qualifying Category II steels are discussed in Sec. 5.2.1. The basic requirements are modified for special situations in which reduced loading rates are assumed (Sec. 5.2.2), the sections used are thin (Sec. 5.2.3) or full-scale destructive testing is performed (Sec. 5.2.4).

5.2.1 Basic Qualifying Procedures (0.625 in. to 4.0 in. thick sections)

The specific recommended criterion for Category II steels in the thickness range from 0.625 to 4.0 in. is:

The NDT temperature of the steel used must be less than the maximum NDT temperature (determined from Fig. 6) for the thickness being used.

In applying this criterion, the NDT temperature of the steel, or its equivalent, may be determined in any of the following ways:

1. By measuring it according to ASTM E-208.

2. By subtracting 50°F from the midpoint of the 5/8 in. DT energy transition curve measured according to ASTM E-604.

3. By selecting the maximum NDT temperature given in Fig. 1 or Table 3.

Figure 6 shows the required NDT temperature as a function of section thickness for both dynamic and reduced loading rates. The curves of Fig. 6 were constructed from Fig. 7 by using the following procedure. Starting with the design thickness, proceed vertically to the $\beta = 0.6$ curve, from there horizontally to the K_{ID}/σ_{yd} curve, and from that

TABLE 5. Category II fracture toughness requirements and criteria for ferritic steels with yield strength no greater than 100 ksi.

Required degree of safety (see Appendix C)	Large margin of safety.
Required amount of fracture toughness (see Sec. 5.2)	Sufficient to prevent fracture initiation of cracks under dynamic loading.

Thickness (B) (in.)	Criteria for meeting toughness requirements[a]
0.625 to 4.0	* With full dynamic loading rates, NDT temperature[b] must be less than a maximum value. See Fig. 6 and Sec. 5.2.1. * With reduced loading rates, NDT temperature can be determined from Fig. 7. See Sec. 5.2.2.
0.19 to 0.625	* Use DT Test E-604-80. 50% or greater shear fracture appearance required at LST. See Sec. 5.2.3. Or * Use DWTT Test E-436. 50% or greater shear fracture appearance required at LST. See Sec. 5.2.3. Or * Use any normalized steel made to "Fine Grain Practice" or better[c]. See Sec. 5.2.3.
Less than 0.19	* No requirements when B is less than 0.19 in. See Sec. 5.2.3.

[a]Full scale destructive testing on a case-by-case basis may be used as an alternate to requirements listed below. See Sec. 5.2.4.

[b]NDT is measured according to ASTM E-208, or an equivalent NDT can be established by subtracting 50°F from the midpoint of the 5/8 in. DT energy transition curve measured according to ASTM E-604 or the NDT temperature requirement can be met by selecting the maximum NDT temperature given in Fig. 1 or Table 3.

[c]Steel with an NDT temperature lower than steels made to a fine grain practice.

point vertically to the A scale on the horizontal axis. The value of the maximum allowable NDT temperature is then equal to the lowest service temperature minus the value of A obtained (i.e., T_{NDT} = LST - A). The example shown in Fig. 7 relates a value of A = 40°F to a plate thickness of 1.5 in.

5.2.2 Qualifying Procedures for Reduced Loading Rates (0.625 in. to 4.0 in. thick sections)

Effective impact limiters have three major characteristics:

1. They provide protection in all drop orientations.

2. They absorb all the kinetic energy from an impact.

3. They dissipate kinetic energy at low force levels (on the order of 50 to 100 times the weight of the container).

For Category II, a temperature shift in the K_{ID}/σ_{yd} reference curve can be introduced if impact limiters are used to reduce the loading rate and protect fracture critical components. These energy absorbers can reduce the loading rate to well below that of the full dynamic level used to establish the K_{ID} curve. For loading rates that produce strain rates on the order of 10^{-1} in./in./s (typical for
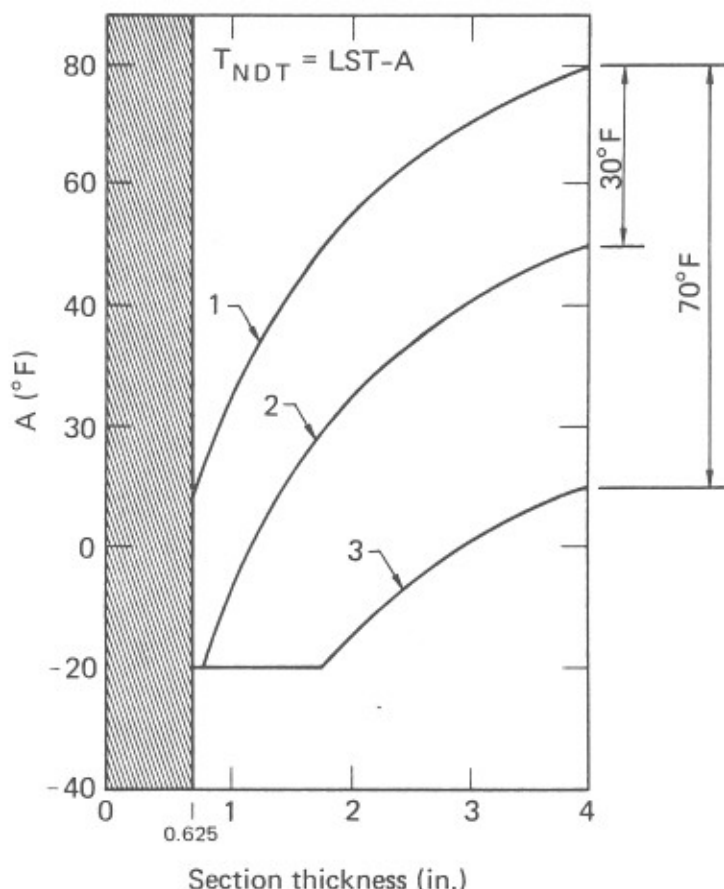
FIG. 6. Design chart for Category II fracture critical components showing reference temperature relative to NDT as a function of section thickness (derived from Fig. 7). Curve 1 is the basic K_{ID}/σ_{yd} curve for $\beta = 0.6$, and represents full dynamic loading with stresses at yield stress level. For effective g loadings of less than approximately 100 g: curve 2, shifted 30°F, may be used for steels with σ_{ys} in the range 60 ksi $\leqslant \sigma_{ys} \leqslant$ 100 ksi; curve 3, shifted 70°F, may be used for steels with σ_{ys} less than 60 ksi.

energy absorbing systems), the appropriate $K_{I(t)}/\sigma_{yd}$ curve shown on Fig. 7 can be used instead of the K_{ID}/σ_{yd} curve to establish the maximum allowable NDT temperature. A temperature shift of 70°F can be used for low strength steels ($\sigma_{ys} <$ 60 ksi); for higher strength steels (60 ksi $\leqslant \sigma_{ys} \leqslant$ 100 ksi), a shift of 30°F can be used.

5.2.3 Qualifying Procedures for Thin Sections (up to 0.625 in. thick)

All sections between 0.19 in. and 0.625 in. thick have the same fracture toughness requirements. Any of the three following methods may be used to qualify Category II steels within this thickness range:

1. Application of full section thickness Dynamic Tear tests as specified in ASTM E-604-80.

Steels will be qualified if 50% shear fracture appearance is achieved at the lowest service temperature.

2. Application of Battelle Drop Weight Tear Tests (ASTM E-436). If at least a 50% shear fracture appearance is observed at the lowest service temperature, then the fracture toughness of the steel is sufficient to qualify it.

3. Use of any normalized steel made to "Fine Grain Practice" or better.

Brittle fracture is not considered a problem for sections less than 0.19 in. thick in Category II, and there are no fracture toughness requirements for these sections.
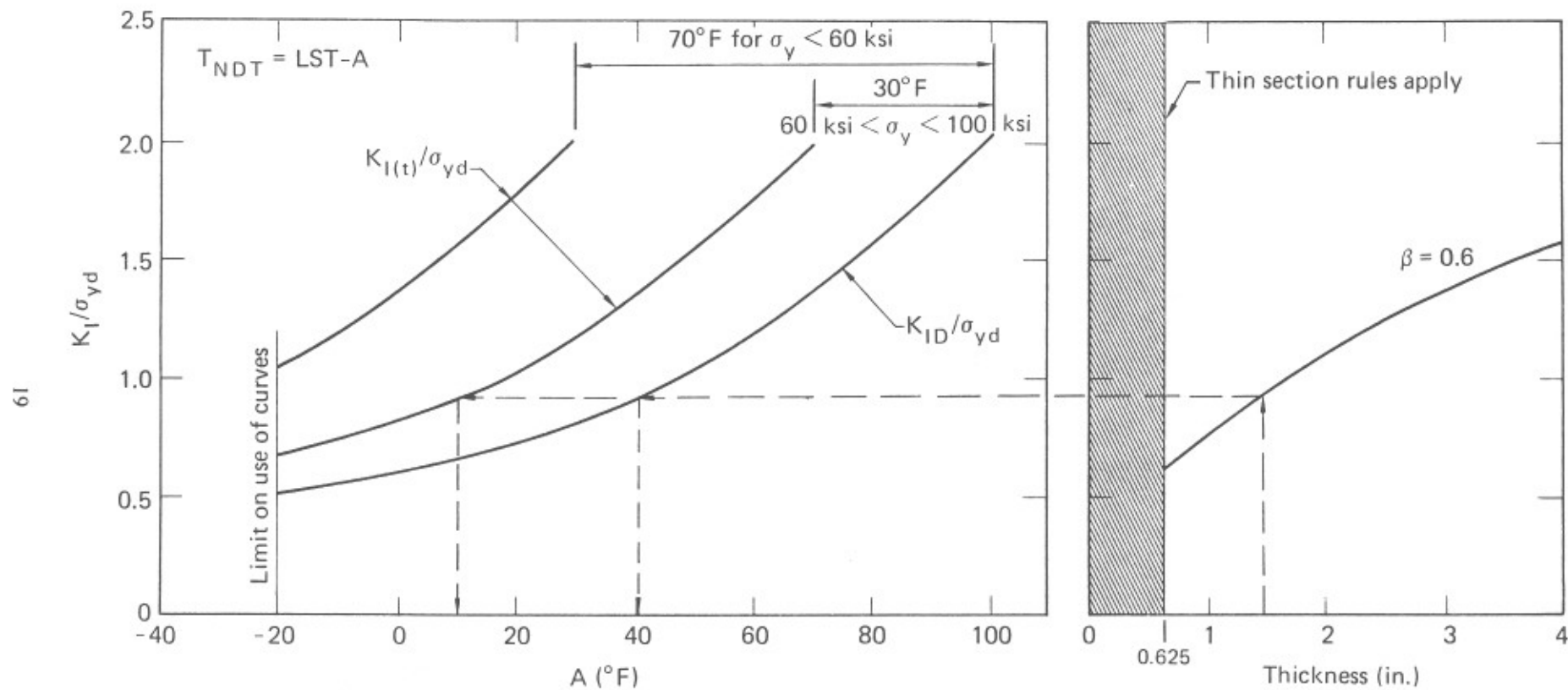
18

FIG. 7. Design chart for Category II fracture critical components.

5.2.4 Qualifying by Full Scale Destructive Testing

Full scale testing can be used to qualify a Category II container design as being resistant to brittle fracture. Testing procedures should be evaluated on a case-by-case basis. Such testing requires the introduction of flaws that are as large and as severe in their orientation and location as any that could credibly be expected to be found from NDE inspection techniques. The material has adequate toughness to protect against brittle fracture if the container does not experience a brittle failure in the fracture-critical components. The required level of toughness is determined by conducting tests on samples from the successfully tested container.

Other containers manufactured to this design must have at least the same fracture toughness as the successfully tested container(s).

5.3 CATEGORY III

The level of safety required for Category III is less than that for Category II. For Category III systems, fracture toughness must be sufficient to prevent fracture initiation at minor defects typical of good fabrication practices. A summary of fracture toughness requirements for Category III steels is shown in Table 6.

Good engineering practices and careful selection of the steel make it reasonable to expect that brittle fracture is unlikely to occur.

TABLE 6. Category III fracture toughness requirements and criteria for ferritic steels with yield strength no greater than 100 ksi.

Required degree of safety (see Appendix C)	Adequate margin of safety.
Required amount of fracture toughness (see Sec. 5)	Sufficient to prevent fracture initiation at minor defects typical of good fabrication practices.

Thickness (B) (in.)	Criteria for meeting toughness requirements
0.4 to 4.0	* Without testing, use any normalized steel made to "Fine Grain Practice" or better[a]. See Sec. 5.3.1. Or * Show that $NDT^b \leqslant 10°F$ ($B \geqslant 0.625$ in.). Or * Test to show that $DT^c \geqslant 50$ ft-lb at $10°F$, with test specimen 0.625 in. thick. Or * Test to show that $C_V^d \geqslant 15$ ft-lb at $10°$. Or * Without testing, use as-rolled steel, provided the welds have been stress relieved and inspected by nondestructive evaluation techniques.
Less than 0.4	* No requirements when B is less than 0.4 in. See Sec. 5.3.2.

[a]Steel with an NDT temperature lower than steels made to a fine grain practice.

[b]NDT is measured according to ASTM E-208, or an equivalent NDT can be established by subtracting 50°F from the midpoint of the 5/8 in. DT energy transition curve measured according to ASTM E-604 or the NDT temperature requirement can be met by selecting the maximum NDT temperature given in Fig. 1 or Table 3.

[c]DT measured according to ASTM E-604, for specimen thickness of 0.625 in.

[d]C_V measured according to ASTM E-23.

5.3.1 Basic Qualifying Procedures (0.4 in. to 4.0 in. thick sections)

Fracture toughness requirements for Category III steels may be met in any of the five following ways:

1. By selecting a steel that is made to a "Fine Grain Practice" or better. No fracture toughness testing is required.

2. By using a steel whose maximum allowable NDT temperature is 10°F.

3. By using a steel whose DT value according to ASTM E-604 is at least 50 ft-lb at 10°F, with a test specimen thickness of 0.625 in.

4. By using a steel whose C_V value according to ASTM E-23 is at least 15 ft-lb at 10°F.

5. As-rolled steels can be used without being qualified by fracture toughness testing provided all welds have been stress relieved and inspected by appropriate nondestructive evaluation techniques.

5.3.2 Qualifying Procedures for Thin Sections (less than 0.4 in. thick)

No fracture toughness criteria are specified for Category III steels less than 0.4 in. thick.

APPENDIX A
FRACTURE MECHANICS

A.1 PRIMARY FACTORS IN BRITTLE FRACTURE

Fracture mechanics has become the principal approach for fracture control and fracture safe design. Application of this approach to engineering structures has been thoroughly reviewed in two recent texts[9,10] to which the reader is referred.

In this appendix, we review fundamental concepts of fracture mechanics basic to the criteria recommended in this report. The more familiar structural failures occur when a yield stress or strain limit is exceeded. However, structural failures may occur suddenly and at nominal stresses below the yield stress of the material. Such failures are identified as brittle fracture failures. Fracture mechanics helps in the study of this less known kind of failure, which occurs because the stress level in the vicinity of a crack has exceeded a critical level. Brittle fracture depends upon the following three primary factors and their interrelationship:

1. *Notch toughness or fracture toughness*, which is a material's ability to absorb energy in the presence of a flaw. Notch or fracture toughness should not be confused with toughness, which is the ability of a material to absorb energy in the absence of defects; toughness in this sense is not directly related to notch or fracture toughness.

2. *Cracks or flaws*, which are initiation points for brittle failures. The larger the flaw, the more likely that fracture will be initiated.

3. *Tensile stresses*, which are a prerequisite for brittle fracture to occur. For a given flaw, the higher the stress component in the crack opening direction (i.e., normal to the crack plane), the greater the chance for brittle failure.

The relationship between fracture toughness, flaw size, and tensile stress is shown schematically in Fig. 8. Each factor is discussed separately in sections to follow.

Several secondary factors also contribute to brittle fracture, but only through their effects on one or more of the primary factors. These secondary factors include temperature, loading rate, fabrication process, heat treatment, production process, stress concentration, residual stresses, fatigue, and environmental effects.

A.1.1 Fracture Toughness

Fracture toughness or notch toughness is the ability of materials to absorb energy in the presence of a flaw. At the tip of a crack, the increase in stress above the nominal stress can be described in terms of a stress intensity factor K_I. When a stress intensity reaches a critical level, the fracture resistance of the material is exceeded and failure occurs. The stress intensity factor under tensile loading is defined by:

$$K_I = C \sigma \sqrt{a} \tag{A-1}$$

where C is a constant for a given specimen and crack geometry, σ is the nominal stress, and a is the flaw size designation. The nominal stress is the stress that is calculated for the flawed region assuming the flaw is not there. It is assumed that the flaw is not large enough to significantly reduce the net section area.

For slow loading and linear elastic conditions, failure occurs when the stress intensity factor (which is a function of stress level and crack size) reaches a critical level. For plane stress conditions, this critical level is designated as K_C. The notation K_{IC} is reserved for the critical stress intensity factor under static loading and plane strain conditions, and K_{ID} for dynamic loading under plane strain conditions. As the material's notch toughness increases and elastic-plastic behavior dominates, toughness can be measured in terms of R-curve resistance, J_{IC} (J-integral), or Crack Opening Displacement tests (COD).

Fracture toughness is a function of both temperature and loading rate (see Fig. 8), as well as specimen thickness. K_{IC} and K_{ID} are both sensitive to microstructural variations introduced during manufacture and fabrication. Because effects of microstructure are strong, a broad range of fracture toughness values
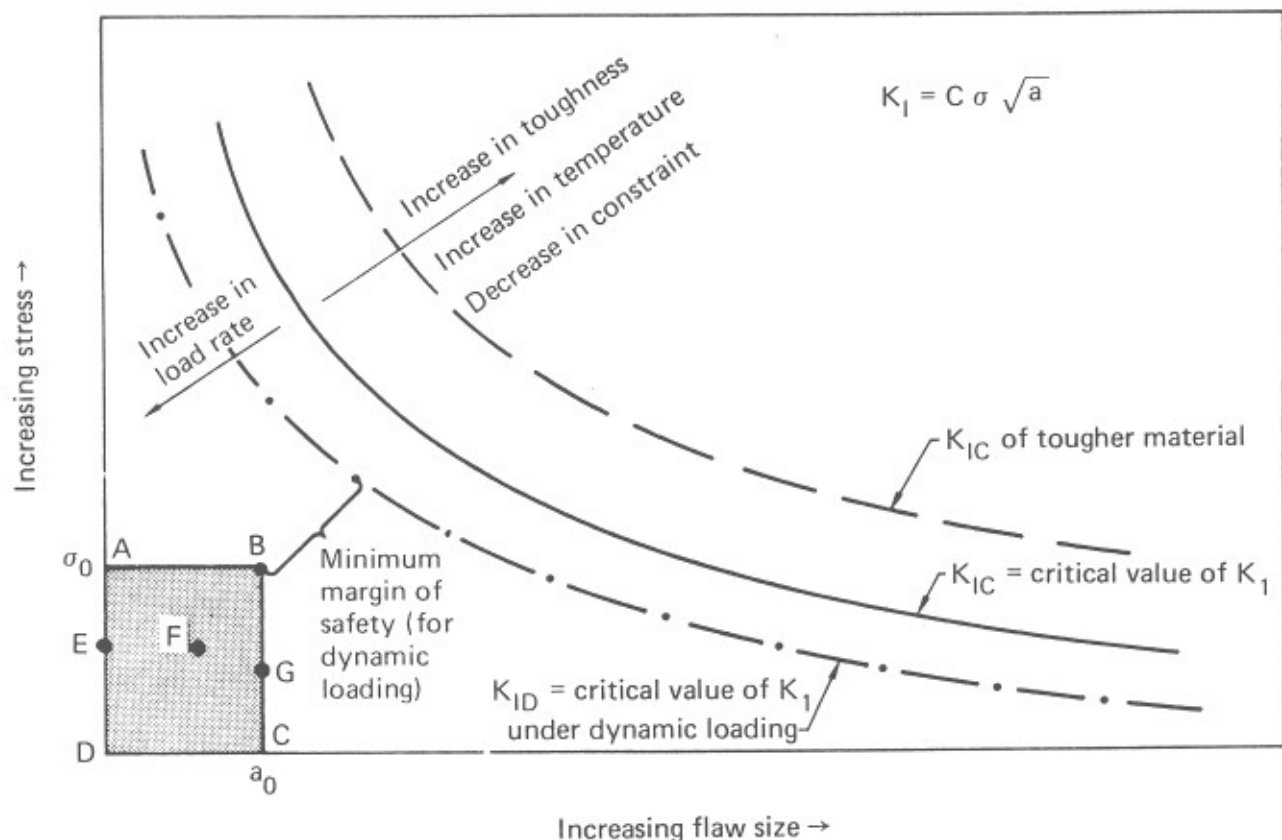
FIG. 8. Schematic relationship of the three primary factors influencing brittle fracture. The secondary effects of temperature, loading rate, and constraint are also shown. If σ_0 is the maximum stress allowable by code and a_0 the maximum flaw size certified for the design, the shaded area contains all points whose stress-flaw size relationship is allowed, from a design point of view. Any toughness curve that does not intersect the shaded area represents a toughness that meets the criteria. The distance from the point B to any given toughness curve indicates the minimum margin of safety for the toughness represented.

is usually obtained for any particular grade or lot of steel. There are no nondestructive techniques for measuring fracture toughness; hence, both specifying minimum fracture toughness levels and requiring fracture toughness testing is generally advisable for all materials used in applications where fracture resistance is critical.

Charpy V-notch and Dynamic Tear tests are notch toughness tests that do not relate the stress level to flaw size as is done for K_{IC} or K_{ID} tests. These tests do, however, show the effects of secondary factors such as temperature and loading rate.

Temperature has a strong effect on the fracture toughness of structural steels, particularly in the transition-temperature range where toughness increases rapidly over a relatively narrow range of temperatures from a "lower shelf" or brittle plane-strain region, through an elastic-plastic region to an "upper shelf" or plastic region where the fracture toughness is generally high enough to preclude brittle fracture. The relationship between fracture toughness and temperature is shown in Figs. 9 and 10 for various toughness tests. The temperature at which the dynamic toughness starts to rise rapidly with increasing temperature corresponds generally to the NDT temperature. At the NDT temperature, the fracture mechanism for 5/8 in. thick specimens starts to shift from the crystallographic cleavage fracture mode to the tougher microvoid coalescence or ductile dimple mode, which is fully developed near the (YC) temperature. Thus, the NDT temperature can be used as an indirect measure of dynamic fracture toughness for structural steels and as a reference point for specifying the level of fracture toughness required (see Appendix B).
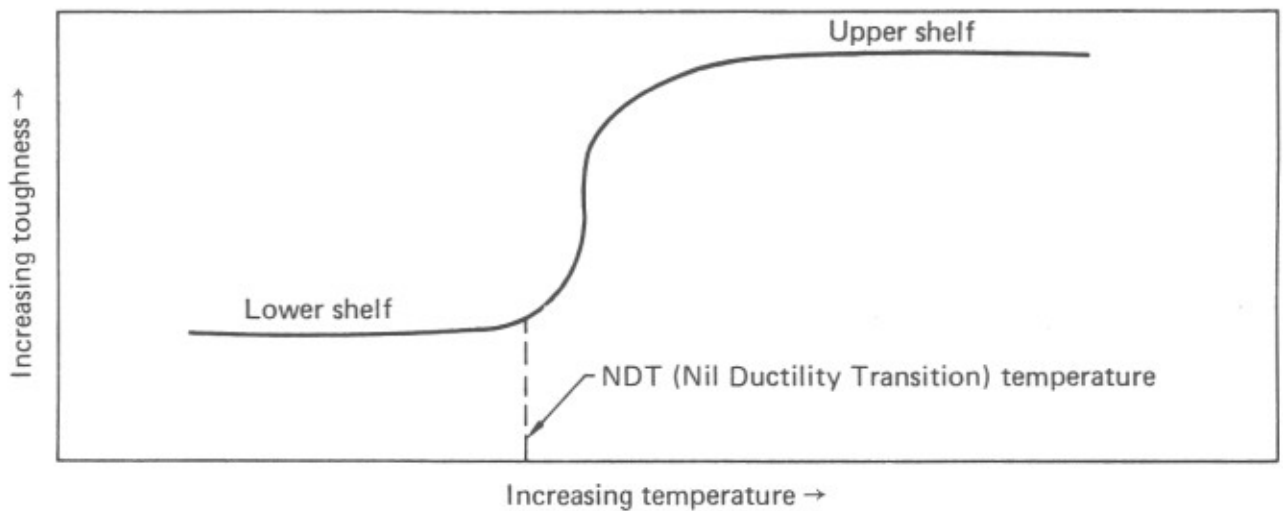
FIG. 9. Influence of increasing temperature on fracture toughness behavior.
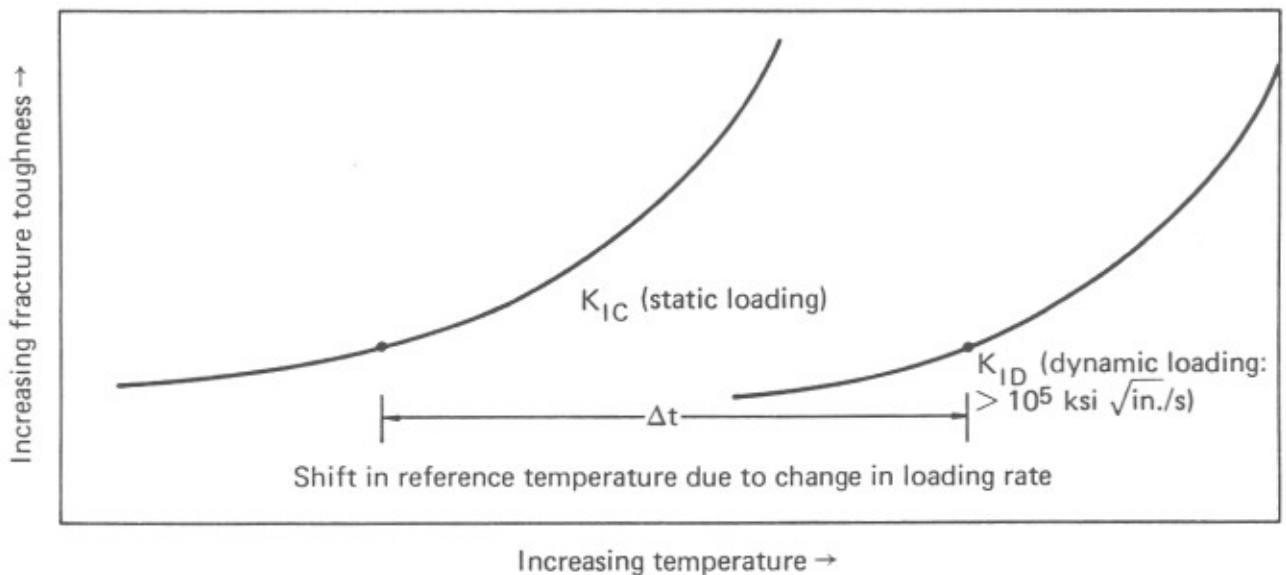
FIG. 10. The effect of loading rate on fracture toughness, expressed in terms of an effective temperature shift.

Loading rate greatly affects the transition temperature of steels having low to intermediate yield strengths. The toughness transition curve for static loading conditions may shift greatly relative to the curve for the same loading applied dynamically. (See Fig. 10.) Dynamic loading rates are generally defined as those having times to fracture of 0.01 s or less or K_I rates in excess of 10^5 ksi $\sqrt{in.}$/s. Fracture times of 1 s or more are taken as static conditions since the static transition curve does not shift to higher temperatures until the fracture time is significantly less than 1 s. The difference in transition temperature between static and dynamic loading decreases linearly as the yield strength increases—from a difference of 160°F at 36 ksi to a difference of 0°F at 140 ksi.

Under static loading conditions, metal in the plastic zone of the crack tip deforms until ductile or cleavage fracture occurs. The size of the plastic zone at fracture is a function of the fracture toughness of the small volume of metal undergoing plastic deformation and the local loading rate in that same region. If for

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any reason there is a small volume of low toughness metal in the deforming region (for example, in-homogeneities in the composition or the microstructure), cleavage fracture may begin at a relatively low nominal stress. Under such conditions, the local loading rate or strain rate in the crack tip region may become dynamic—even though the overall structure is undergoing static loading. Small "pop-in" cracks may start at local inhomogeneities, as just described, or in regions with large residual-stress gradients, such as at welds. These cracks may behave as though the entire structure were being dynamically loaded. Considerable technical debate exists concerning what precise service conditions are associated with "pop-ins." However, to be conservative in Category I applications, dynamic loading is assumed.

Metallurgically, fracture toughness is strongly influenced by the microstructure. In turn, microstructure is related to section thickness, which has a large effect on cooling rates during heat treatment. Also, the microstructure is influenced by section thickness through compositional and microstructural gradients introduced by steel mill practices. Generally thinner sections have a finer, more uniform microstructure and therefore a higher inherent fracture toughness, as well as less constraint.

A.1.2 Crack or Flaw Size

Cracks and flaws, which are present in all real structures, perturb the local stress field. The fact that principal stresses become infinitely large at the tip of a zero-root-radius crack (according to elastic stress-field calculations) means that some plastic flow must occur at a crack tip when the local stress near the tip reaches the yield level. This "blunting" of the crack modifies the local stress field. As the load increases, a plastic zone expands ahead of and around the crack tip. The size of the plastic zone at the time that fracture begins is a measure of the material's fracture toughness. As shown in Eq. A-1, the nominal stress necessary to initiate fracture is a function of crack size and fracture toughness. The crack simply intensifies the stress at its leading edge by the influence of the geometry on the stress field. When this intensification factor K_I reaches the critical level K_{IC}, fracture occurs.

As used in Eq. A-1, crack size is generally defined as the depth of an edge crack, or one-half the width of a crack through the thickness. Surface cracks, internal cracks, and flaws that have other geometries are incorporated into Eq. A-1 by the characteristic length "a" and by the constant C, which is itself a function of flaw shape and orientation. Generally the size, geometry, orientation, and location of the flaw that will initiate fracture—that is, the flaw that will lead to failure—is unknown. Worst-case geometric combinations can be postulated, however, and the size of the critical flaw can be calculated by Eq. A-1 for any particular combination of fracture toughness and stress. To be conservative and to compensate for uncertainties in non-destructive testing capabilities, the largest flaw that can be tolerated is usually taken to be considerably smaller than the calculated critical size.

For design purposes, it is appropriate to assume the existence of a specific size, shape, and orientation of a flaw or crack. Examples of different shapes of flaws are shown in Fig. 11, along with the stress intensity factor for each geometry. Should actual flaws be discovered using nondestructive evaluation techniques, the specific size, geometry, orientation, and location of those flaws should be used to evaluate the structure's susceptibility to brittle failure.

In addition, the growth of flaws under fatigue conditions should be evaluated. Techniques for evaluating crack growth caused by fatigue can be found in Ref. 9.

A.1.3 Tensile Stress

The third primary factor in brittle fracture is the nominal stress defined in Eq. A-1; that is, the tensile stress calculated for the crack tip region with no cracks present. The stress intensification produced by the crack will lead to yielding at the root (i.e., the tip) of the crack under any tensile loading. As the nominal stress is increased, the size of the plastic zone increases, and fracture occurs at the critical stress intensity. If the amount of plastic deformation in the crack tip region preceding fracture is small (low fracture toughness), the deformation is considered to occur under plane strain conditions (maximum constraint), and the linear-elastic stress assumption of Eq. A-1 is valid up to the point of fracture instability.

Surface crack
$K_I = 1.12 \, \sigma \, \sqrt{\pi a / Q}$
Where $Q = f(a/2c, \sigma)$
from graph below

Through thickness crack
$K_I = \sigma \, \sqrt{\pi a}$

Edge crack
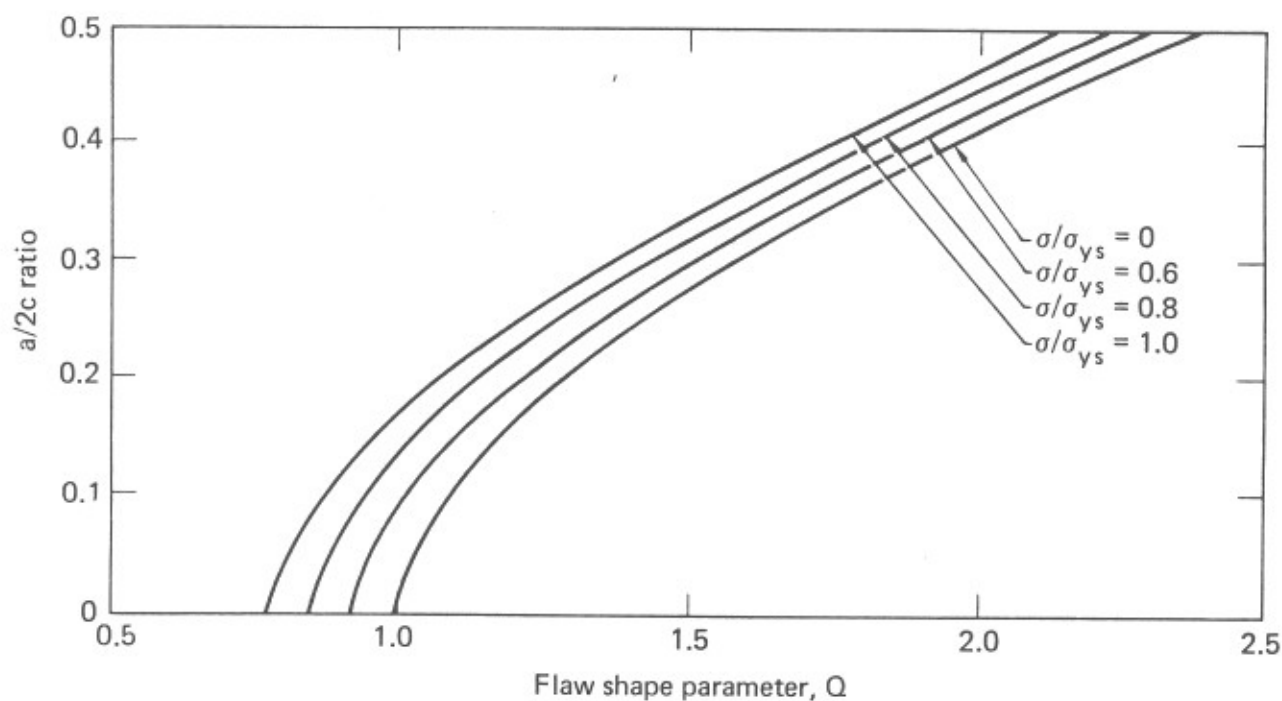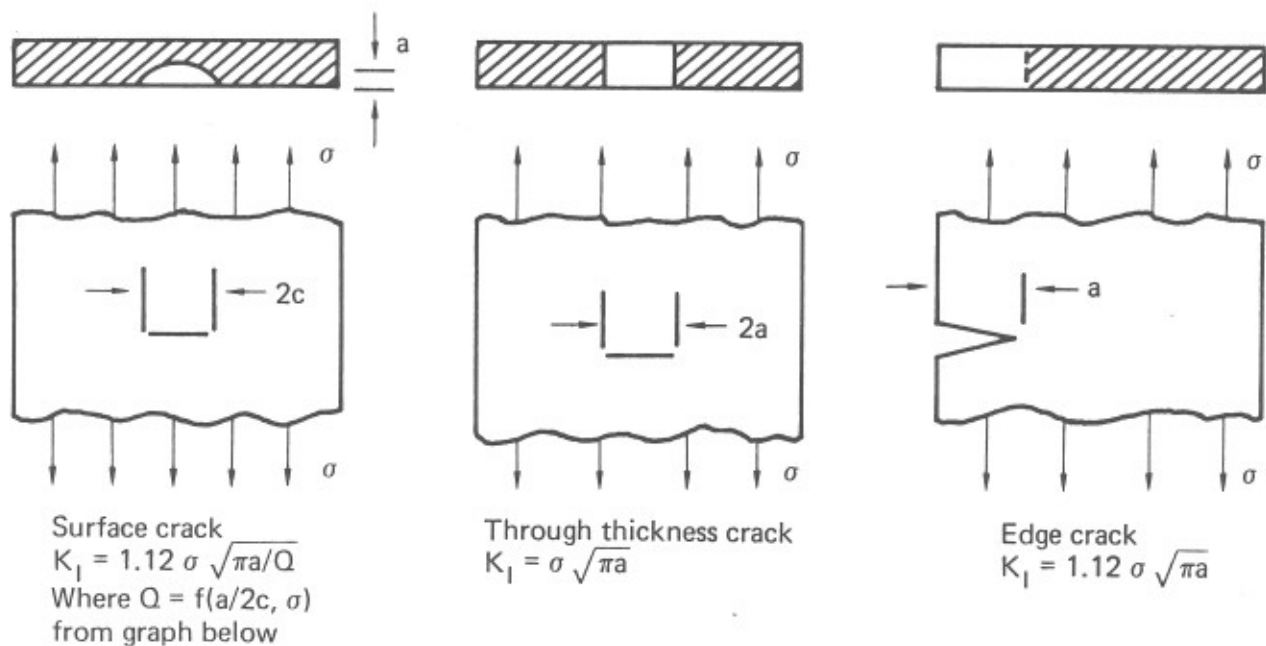$K_I = 1.12 \, \sigma \, \sqrt{\pi a}$

FIG. 11. Stress intensity factors for different crack geometries.

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The true measure of the material's fracture toughness is K_{IC}. When an axial stress is applied to a K_{IC} test specimen, a three dimensional state of tensile stress develops at the tip of the crack because of the specimen's thickness and the effects of Poisson's ratio. This is the plane strain condition.

However, the level of tensile stress that is normal to both the applied load and the plate diminishes with decreasing plate thickness. For very thin plates, the stress normal to the plate becomes nearly zero. Because of this small tensile stress normal to the load, a plane stress condition can be assumed for thin plates. Under plane stress conditions, large shear stresses develop far beyond the tip of the crack and brittle failure will not occur. Section thickness, therefore, can have a profound or even dominant effect on brittle fracture.

Whenever fracture toughness tests are conducted it is desirable that plane strain conditions exist (i.e., all three components of tensile stress are developed). When testing tougher materials, test specimens need to be thicker in order to maintain plane strain conditions and induce a brittle fracture.

The ASTM test for K_{IC} (E-399) specifies that the plate thickness B must satisfy:

$$B \geq 2.5 (K_{IC}/\sigma_{ys})^2$$

where B is the section thickness, K_{IC} is the measured fracture toughness, and σ_{ys} is the static yield stress of the material. This relation defines the limit or boundary between plane strain conditions (to which linear elastic fracture mechanics applies), and the beginning of elastic-plastic behavior (at which time the plastic zone at the tip of the crack begins to enlarge).

Hahn and Rosenfield[11] observed that a significant increase in plastic behavior occurs when the plate thickness satisfies, for a value of $\beta = 1.0$, the inequality:

$$B \leq \frac{1}{\beta}(K_{ID}/\sigma_{yd})^2 \quad . \tag{A-2}$$

A fracture under these conditions is preceded by extensive, through-thickness yielding.

In plates whose thickness B satisfies Eq. A-2, the lateral constraint is relaxed, the triaxial state of stress at the crack tip decreases, and fracture resistance increases as the stress state changes from plane strain to plane stress. For sufficiently thin sections, the fracture becomes entirely plastic. This increased resistance to fracture occurs even though the inherent metallurgical characteristics, including K_{IC}, are unchanged.

Yield stress is not directly related to the maximum toughness for steels with static yield strengths below about 100 ksi. However, the static or dynamic yield strength is correlated to K_{IC} or K_{ID} at the NDT temperature. This correlation was first postulated analytically by Irwin[12] as, at NDT temperature:

$$K_{ID} = 0.78 \, \sigma_{yd} \sqrt{in.} \quad .$$

Shoemaker and Rolfe[13] observed that at the NDT temperature, a 1 in. thick K_{IC} specimen tested under impact ceases to satisfy the ASTM requirements for valid K_{IC} tests. From their observations, they determined that, at NDT temperature:

$$K_{ID} = 0.64 \, \sigma_{yd} \sqrt{in.} \quad .$$

Rolfe[9] recommends the following relationship at NDT temperature:

$$K_{ID} = 0.6 \, \sigma_{yd} \sqrt{in.} \quad .$$

This last relationship between K_{ID} and the dynamic yield stress will effectively move a K_{ID}-versus-temperature curve up or down in proportion to a material's yield stress. Therefore, for steels with static yield strengths less than 100 ksi, a K_{ID} or K_{IC}-versus-temperature curve normalized by the proper yield stress can be used for fracture mechanics purposes.

For steels that have been heat treated to yield strengths higher than 100 ksi, a "strength transition" occurs in which the maximum fracture toughness (the upper shelf) decreases rapidly with increasing yield strength. For quenched and tempered steels of high strength, the upper shelf toughness level generally controls fracture behavior; therefore, to prevent brittle fracture, it is necessary to determine that both (1) the transition temperature is low enough and (2) the upper shelf toughness is high enough. For steels having low static yield strength, low "upper-shelf" toughness is seldom a problem, and fracture toughness levels can be characterized entirely by the NDT temperature, as discussed earlier.

A.2 SECONDARY FACTORS

The effects of temperature, and loading rate, are discussed in A.1.

Effects of production, fabrication, joining, and heat treating processes on the fracture toughness of steel can also contribute to brittle fracture. Each process directly affects the microstructure and can also generate residual stresses and cracks, which are primary factors in brittle fracture.

Fatigue, stress corrosion, and other environmental effects provide mechanisms for slow crack extension (subcritical crack growth), and hence contribute to possible brittle fracture. When a crack grows to the size that is critical for the nominal stress present, fracture occurs.

APPENDIX B
FRACTURE SAFE DESIGN

W. S. Pellini prepared "Guidelines for Fracture-Safe Design of Steel Structures"[3] and "Manual of Engineering Procedures for Fracture-Safe Design"[8] as design-reference documents for the AAR. This appendix is a synopsis of the principles present in these two documents, which provide analysis systems and procedures in a form typical of ASME codes and standards. The Guidelines are based on procedures defined as design-by-analysis and are compatible with procedures given in the ASME Nuclear Pressure Vessel Code, Sec. III, Div. I. We believe that the guidelines are particularly useful in evaluating and controlling the potential for brittle fracture in shipping containers for radioactive materials.

The AAR guidelines were developed for designs using ferritic steels in the transition temperature range. Yield strengths ranging from 36 to 120 ksi and section thicknesses from 1/2- to 4-in. are considered. Dynamic loading rates and slow-to-intermediate loading rates are treated separately, and there are separate sections on steels with low-to-intermediate strength (36 to 70 ksi yield strength), high-strength steels (80 to 120 ksi yield strength), and primary structural welds. In each case, the designer has several options that depend on his assessment of the consequences of failure and the degree of conservatism required. Selection of options determines the level of fracture toughness required to control or prevent structural failure by brittle fracture. The designer's choice is then embodied in the steel specifications, processing, heat treatment, fracture toughness testing, and quality assurance certification.

For cases where loading is dynamic, the AAR guidelines require that the designer first select either the "fracture-arrest principle" or the "fracture-initiation principle" as the design option. If the fracture-arrest option is selected, the toughness of the steel is to be specified high enough to stop a moving, through-thickness crack. With this high level of toughness, an existing through-thickness crack cannot initiate (start to move) at the specified nominal stress, because if there is enough toughness to stop a moving crack of the same size, there must be more than enough toughness to prevent a large pre-existing crack from starting to move.

The guidelines procedure for assuring fracture-arrest behavior starts with a lower-bound K_{ID}-versus-relative temperature curve (Fig. 2) similar to the K_{IR} curve used in Section III, Appendix G, of the ASME Nuclear Pressure Vessel Code. The curvature of Fig. 2 is assumed to be constant for all structural steels considered and is based on the lower bound results of dynamic fracture toughness tests conducted at Westinghouse Electric Corporation with specimens up to 8 in. thick.[14] The curve is also the lower bound of data given in Fig. 6.21 of Ref. 9. The curve is shifted along the temperature scale (relative to the static data) but the curvature is essentially the same as that obtained in valid K_{IC} tests with specimens up to 12 in. thick.[15] The NDT temperature (relative temperature = zero) is located on the relative temperature scale where the toughness level is 40 ksi $\sqrt{in.}$; that is, the curve is shifted horizontally so that the NDT temperature corresponds with K_{ID} = 40 ksi $\sqrt{in}$. This, in effect, defines NDT as the temperature where K_{ID} = 40 ksi $\sqrt{in}$. For steels with σ_{ys} = 60 ksi or less, this is a fairly accurate approximation, but as σ_{ys} increases, the approximation becomes less accurate.

For a particular section thickness, two other points are also located on the curve (Fig. 4). Point (L) is the upper temperature limit for plane-strain or fully elastic behavior, and (YC) the lower temperature limit for fully plastic behavior. At temperatures above (YC), yield level (plastic) stresses are required for slow extension of a ductile fracture. Below the (L) temperature, linear elastic fracture mechanics analyses are applicable and all fractures are brittle after initiation. At temperatures between (L) and (YC), the steel exhibits elastic-plastic properties, with crack arrest occurring at nominal stresses that increase approximately linearly with temperatures (Fig. 4) from approximately $0.2\,\sigma_{ys}$ at (L) to $1.0\,\sigma_{ys}$ at (YC).

The toughness levels at which the (L) and (YC) points are located on the design-reference curve of Fig. 4 are a function of section thickness and dynamic yield strength, as follows:

At (L), β = 0.4
At (YC), β = 1.0

where β = dimensionless parameter = $\frac{1}{B}\left(\frac{K_{ID}}{\sigma_{yd}}\right)^2$

and

$\quad\quad B$ = section thickness (in.)
$\quad\quad \sigma_{yd}$ = dynamic yield stress (ksi)
$\quad\quad K_{ID}$ = dynamic fracture toughness (ksi $\sqrt{in.}$)

From the above relationships, the toughness level is found to be:

$$K_{ID} = \sigma_{yd}(\beta B)^{1/2} \quad .$$

At both (L) and (YC), the value of σ_{yd} is considered constant at about 70 ksi in the AAR guidelines.

On a graph of nominal stress at fracture versus temperature (Fig. 4), the points (L), (0.5 YC), and (YC) can be located and joined by a steeply rising straight line. At temperatures below (L), the line is nearly horizontal with the stress dropping slowly from approximately 0.2 σ_{ys} at (L) to less than 0.1 σ_{ys} at 100°F below NDT temperature. Fracture-arrest conditions are met if the combination of temperature and nominal stress places the structure to the right of this "Fracture-Arrest Curve."

To select a steel with enough toughness to meet the crack arrest criteria (have a sufficiently low NDT temperature), the nominal design stress acting normal to the expected fracture path(s) must be known, and a lowest service temperature must be selected. If the designer has reason to expect "abusive" service loading (accidents, etc.), then high service stresses (yield level) should be anticipated, and the steel should have (YC) properties. To achieve this level of toughness, the (YC) temperature relative to NDT (on the K_{ID} versus relative-temperature curve, Fig. 4) is subtracted from the lowest service temperature to define the maximum NDT temperature required of the steel. For nonabusive conditions, (0.5 YC) properties are adequate, and the (0.5 YC) relative temperature is subtracted from the lowest service temperature to define the maximum NDT temperature of the steel.

Fracture toughness testing to determine the NDT temperature is optional in the guidelines system since there is sufficient toughness data available to plot the statistical distribution of NDT temperature for each of seven categories of structural steels (Fig. 1). Using the high end of these distribution bands, the designer can confidently select a steel that has an NDT temperature below the temperature required for fracture arrest. The confidence level can be significantly increased, however, and it will generally be possible to use a lower grade steel (steel with NDT in the lower portion of the distribution band) by specifying fracture-toughness certification procedures for each fracture-critical component.

When the prevention of fracture initiation is selected as the design option, initiation is expected to result in brittle fracture, and the steel is assumed to behave in an elastic manner at stresses up to the point of fracture. Using this option, fracture mechanics can be applied with the objective of selecting steels that will have sufficient toughness at the LST so that the fracture-critical crack size (the crack size that is calculated to result in fracture initiation) will be significantly larger than the design-reference crack size. This requires very precise stress analysis and inspection, particularly in the regions where crack initiation might occur. Note that "use of the fracture initiation principle for fracture-critical structures is feasible only when high assurance can be placed on precluding the presence of fracture-critical crack sizes."

The AAR guidelines system applies a safety factor on crack size by defining the design-reference crack as two to three times the size of the largest structural crack that is expected to be present in the structure. This structural crack size is selected on the basis that reliable, fully qualified nondestructive inspection techniques will be used to certify that larger cracks will not be present. If it is not possible to certify that larger cracks will be absent, the fracture arrest criteria should be used.

The fracture-critical crack size is the crack size that is calculated to result in fracture initiation. Formulas and graphical techniques for calculating critical crack sizes as a function of crack geometry and stress level are given in the guidelines. The calculation is made for the LST, using the design-reference curve (K_{ID}-versus-relative temperature) and the local stress (crack-opening stress) that applies at the assumed site of the crack.

The allowable size difference between the design-reference and calculated fracture-critical crack sizes should be decided by the degree of fracture-safe assurance required and the degree of confidence in the inspection techniques.

APPENDIX C
MARGIN OF SAFETY

Interrelationships among factors that bear upon the margin of safety from brittle fracture are shown in Fig. 8. For any given container, or container component, allowable stresses are usually specified by appropriate codes. Therefore, there is a maximum stress level that may appear, represented by the horizontal line through point A. Similarly, a maximum flaw size is certified for the design; the vertical line through point C represents that maximum. The shaded area bounded by points A, B, C, and D represents the design-allowable region. Any combination of stress and flaw size in the system may be represented as a point in the region ABCD (e.g., points E, F, G). Point B represents the worst condition of maximum flaw size at a point of maximum allowable stress, a combination which may not be present in the actual system.

The fracture toughness curve K_{IC} shown is assumed to be known for a given steel. As will be discussed in the following, dynamic loading rates shift the curve to the position of the K_{ID} curve shown. A further shift to the "worst case" position represents the temperature effects when the lowest service temperature is assumed. If the worst case curve does not intersect the shaded area, the steel is considered safe for the application. The distance from B to the worst case curve represents the minimum margin of safety (under plane strain conditions). For applications in which the actual stress-flaw size combinations are represented by points further from the worst case curve (e.g., points E, F, and G), the margin of safety will be greater. Points on the vertical axis (i.e., where the flaw size is zero) are likely to predominate in any given component.

The criteria established in the text for three categories of safety from brittle fracture can be rationalized in terms of six factors affecting fracture behavior (Appendix A). Of these six factors, three are primary (toughness, stress, and flaw size) while the other three are secondary in that they all cause changes in the effective toughness or fracture behavior (temperature, loading rate, and constraint). The contribution of each of these factors to fracture safety can be discussed separately and their total effect can be used to define an overall margin of safety as indicated in Fig. 8; i.e., the minimum distance between a typical point F representing the existing stress level and flaw size, and the curve that represents toughness under existing conditions.

The position of the toughness curve is determined by the factors affecting fracture toughness, and the region under the curve can be viewed as the safe zone in which brittle fracture will not occur. It is obvious that the minimum margin of safety is zero when the point B lies on the curve representing the fracture toughness of the steel (Fig. 8). The margin of safety can be increased by:

1. Increasing the fracture toughness of the steel (i.e., moving the toughness curve upward to the right).
2. Decreasing the stress (i.e., moving point B vertically downward).
3. Decreasing the crack size (i.e., moving point B to the left).

The fracture toughness itself can be increased by:

1. Raising the temperature.
2. Decreasing the loading rate.
3. Decreasing the constraint, i.e., by using sections that are thinner than the minimum thickness required to achieve plane strain conditions ($\beta = 0.4$).

Each of these actions increases the margin of safety as defined above. Further improvements in margin of safety can be expected if the flaw geometry, orientation and location are less than the assumed "worst case," i.e., if the flaw is not very sharp (does not have a root of zero radius), the flaw is not located in the region of maximum stress, or the plane of the crack is not oriented normal to the principle tensile stress.

To be conservative, we assume the worst case conditions on flaw shape, location and orientation in all three categories, with the expectation that real cases will be less severe and will therefore provide an extra margin of safety. An additional bonus is also expected from the assumption that metal temperatures will be abnormally low during the hypothetical accident—a combination of conditions unlikely to occur.

The contributions of the above factors to the margin of safety for each of the categories are discussed in more detail below.

Category I: The largest margin of safety is assured for Category I by requiring enough toughness so that through-thickness flaws will arrest under dynamic loading conditions, with stresses as high as the yield stress, and when metal temperatures are low (at LST). That is, point B (Fig. 8) must remain in the safe zone (below the curve) for large flaws at high stresses even when the toughness curve is displaced downward by a high loading rate, low temperature, and the partial constraint ($\beta = 1.0$) assumed for this category. Loading rates and stresses will be high only during hypothetical accident conditions. The shock mitigation system will probably decrease the loading rate below the dynamic conditions assumed, and in most cases mitigation systems will also hold the maximum stress to less than the assumed value. Both of these factors will contribute greatly to the margin of safety. The likelihood that large flaws will be detected and eliminated also adds considerably to the margin. Under actual conditions the point B will very probably be displaced far to the left to meet the stringent NDE requirements.

The requirement that toughness testing be carried out on the steels used in all fracture critical components in Category I, combined with the fact that the curve in Fig. 3 is based on lower bound K_{ID} data (Fig. 2) adds assurance that the location of the toughness curve in Fig. 8 is conservative, i.e., the true fracture toughness of the material under consideration is probably higher than assumed; therefore, the margin of safety is conservative.

Category II: The zone of safety for Category II, although large, is smaller than for Category I, primarily because the criteria for Category II steels require only sufficient toughness to prevent initiation of cracks, rather than enough toughness to stop moving cracks (the fracture-arrest criteria for Category I steels). This reduction in required toughness moves the curve in Fig. 8 downward and toward the left. Therefore, in Category II, the tolerable flaw sizes may not be as large as in Category I (because of the reduced zone of safety), and flaw size control becomes a major concern. In this category, control of brittle fracture depends on controlling flaw size and stress (i.e., preventing fracture initiation), rather than depending on the toughness of the steel to arrest moving cracks, as in Category I.

A further reduction in the zone of safety relative to that achieved in Category I results from the allowance for a shift in the K_{ID} curve to lower temperatures when it can be shown that the shock absorbing system will reduce the loading rate to an intermediate value. Credit for this reduced loading rate is allowed in Category II, and lower fracture toughness is permitted than would be considered adequate for Category I.

Category III: In this category, steels are to be selected with sufficient toughness to preclude fracture initiation at minor defects that are typical of good fabrication practices. Good fabrication will always provide a positive margin of safety. Point B in Fig. 8 is assumed to be far to the left in the safe zone, where the curve is high. However, the combination of stress, flaw size, and fracture toughness may not always provide a large margin of safety under severe operating conditions.

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HFK/km

GLOSSARY

Brittle fracture Crack propagation at nominal stresses below the yield stress of the material.

Containment vessel The receptacle on which principal reliance is placed to retain the radioactive material during transport.

Ferritic steel Steel with a microstructure that is predominately ferrite ("ferrite: a solid solution of one or more elements in body-centered cubic iron," *Metals Handbook*, 8th Ed.)

Fracture-arrest conditions Combinations of nominal stress and toughness that will stop a propagating crack.

Fracture-critical component A component whose failure by fracture could lead to penetration or rupture of the containment system.

Lower shelf Temperature-independent low-toughness level below the transition temperature range.

Nominal stress The maximum principal tensile stress at a point in the absence of a flaw—considering primary stresses as defined in *Regulatory Guide* 7.6 and secondary membrane stresses that exist over a substantial portion of the structure.

Transition temperature A narrow temperature range in which the toughness increases rapidly with temperature from a lower to an upper shelf level.

Upper shelf Temperature-independent high-toughness level above the transition temperature range.